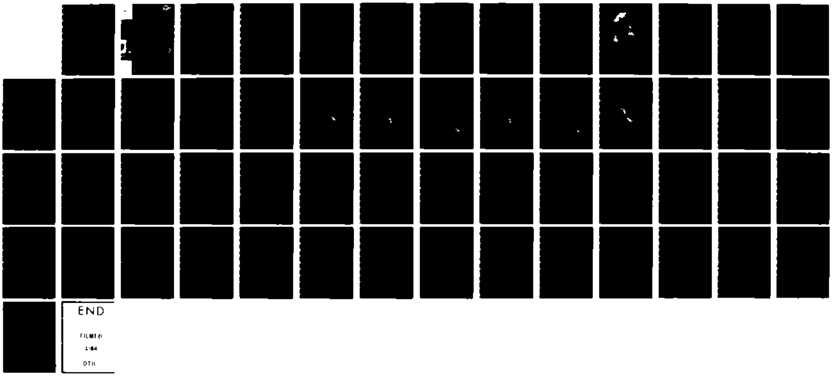
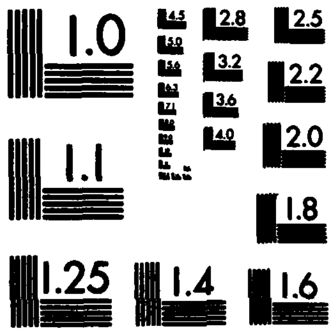
AD-A135 520 SEDIMENTATION STUDY FOR THE ROCHESTER MINNESOTA FLOOD-CONTROL PROJECT(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS HYDRAULICS LAB 1/1

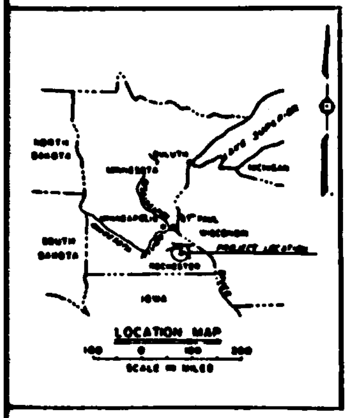
UNCLASSIFIED D T WIILIAMS OCT 83 WES/MP/HL-83-7 F/G 8/8 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

US Army Corps
of Engineers



AD-A135 520

MISCELLANEOUS PAPER HL-83-7

SEDIMENTATION STUDY FOR THE ROCHESTER, MINNESOTA, FLOOD-CONTROL PROJECT

by

David T. Williams
Hydraulics Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

DTIC
ELECTE
DEC 7 1983
S D
D

October 1983
Final Report

Approved For Public Release; Distribution Unlimited

DTIC FILE COPY

HYDRAULICS
LABORATORY

Prepared for U. S. Army Engineer District, St. Paul
St. Paul, Minn. 55101

83 12 07 002

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper HL-83-7	2. GOVT ACCESSION NO. AD-A135 520	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SEDIMENTATION STUDY FOR THE ROCHESTER, MINNESOTA, FLOOD-CONTROL PROJECT		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David T. Williams		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Hydraulics Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer District, St. Paul 1135 USPO and Custom House St. Paul, Minn. 55101		12. REPORT DATE October 1983
		13. NUMBER OF PAGES 51
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computer programs
Flood control
HEC-6 Computer program
Rochester, Minnesota
Sedimentation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The U. S. Army Engineer District, St. Paul (NCS), and the Soil Conservation Service (SCS) have planned a combined flood-control project for Rochester, Minnesota, involving the construction of upland reservoirs, channel modifications, levees, and other structural features as well as floodplain regulation changes to reduce the flooding hazard. The channel modifications include combinations of general channel widening, increasing channel slope by channel straightening, and decreasing channel roughness by clearing and grubbing that

(Continued)

20. ABSTRACT (Continued).

occur with channel enlargement. NCS asked the U. S. Army Engineer Waterways Experiment Station (WES) to determine the impacts of proposed channel modification and impoundments on the sediment transport characteristcs of the South Fork Zumbro River and two of its tributaries, Cascade and Bear Creeks.

To accomplish these objectives, the "Network" version of the computer program, "HEC-6, Scour and Deposition in Rivers and Reservoirs," was used to model the South Fork Zumbro River and Cascade and Bear Creeks as a linked system with another tributary, Silver Creek, as a local inflow point.

An HEC-6 model of the system was calibrated using historic data and judgment and verified by comparison of the sediment movement of the prototype and model using the 1978 flood of record as the test. A model of the proposed conditions was calibrated by changing geometry, sediment parameters, and hydrology to simulate the modification. The simulation of future sedimentation conditions of the system revealed several significant items.

a. Scour and deposition in the system for a 6.5-year proposed conditions simulation did not cause the design water-surface elevations to be exceeded at any point in the system. In general, scour and deposition were not significant enough to endanger project performance.

b. The Standard Project Flood (SPF) simulation of the proposed condition did not cause the water-surface elevation to exceed existing conditions SPF water-surface elevations.

c. Silver Lake, a small reservoir in the system, will have its deposition rate reduced from 7,300 to 1,900 cu yd/yr mainly due to increased hydraulic efficiency.

d. Although the sediment being delivered to the system is reduced due to proposed reservoirs and land treatment, the increased hydraulic and sediment transport efficiency will cause the sedimentation rate downstream of the project to increase by 31 percent.

Sensitivity tests were made by varying sediment and geometric parameters and results were analyzed for project performance.

PREFACE

The sedimentation study of the Rochester, Minnesota, flood-control project, documented by this report, was performed for the U. S. Army Engineer District, St. Paul.

The study was conducted in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) during the period May 1980 to August 1983 under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and M. B. Boyd, Chief of the Hydraulic Analysis Division, and under the general supervision of Mr. W. A. Thomas, Math Modeling Group. The work was performed and the report was written by Mr. D. T. Williams of the Math Modeling Group.

Commanders and Directors of WES during the conduct of this work and the preparation and publication of this report were COL Nelson J. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

SEDIMENTATION STUDY FOR THE

ROCHESTER, MINNESOTA, FLOOD-CONTROL PROJECT

PART I: INTRODUCTION

Problem Description

1. The city of Rochester is located in Omsted County in the southeastern part of Minnesota. The South Fork Zumbro River flows through the city where it merges with Bear, Cascade, and Silver Creeks (Figure 1). The South Fork Zumbro River has a history of flooding problems ranging from the first reliable accounting of a flood in 1855 to the recent July 1978 flood of record. The 1978 flood caused extensive property damage and claimed five lives.

2. In a cooperative effort, the U. S. Army Engineer District, St. Paul (NCS), and the Soil Conservation Service (SCS) planned a combined flood-control project (described in U. S. Army Engineer District, St. Paul, 1982) with the SCS constructing three reservoirs on Cascade Creek, three on Bear Creek, and one on Silver Creek as shown in Figure 2. Table 1 shows the relative drainage areas of each tributary and main stem as well as the drainage area and capacity of each of the reservoirs. A part of the SCS portion of the project is land treatment to aid in erosion control of the drainage basin.

3. NCS has proposed channel modifications, levees, and other structural features as well as floodplain regulation changes to reduce the flooding hazard. Channel modifications include combinations of general channel widening, increasing channel slope by channel straightening, and decreasing channel roughness by clearing and grubbing that occur with channel enlargement.

4. At the onset of the study, suggestions were made to NCS by the U. S. Army Engineer Waterways Experiment Station (WES) on features of the design to minimize sediment impacts. Some important points were:

- a. Keep a consistent water velocity throughout the project for a range of flood discharges with increasing velocity for increasing discharges.
- b. Keep the same percentage of flow in overbanks and channels for all flows when possible.
- c. Use a low-flow channel when practical.
- d. Align the design channel with the existing channel as much as possible.

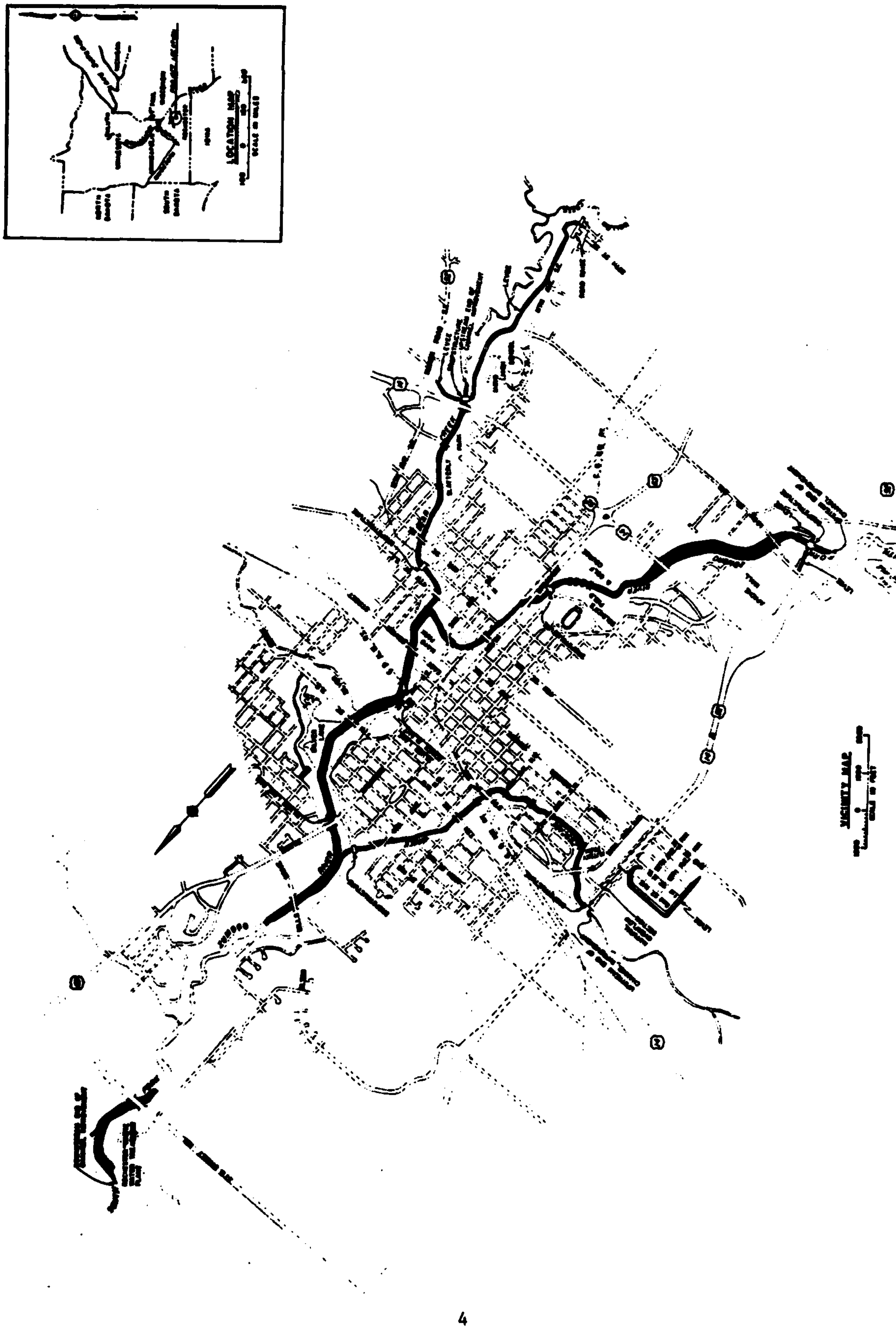


Figure 1. Project location.

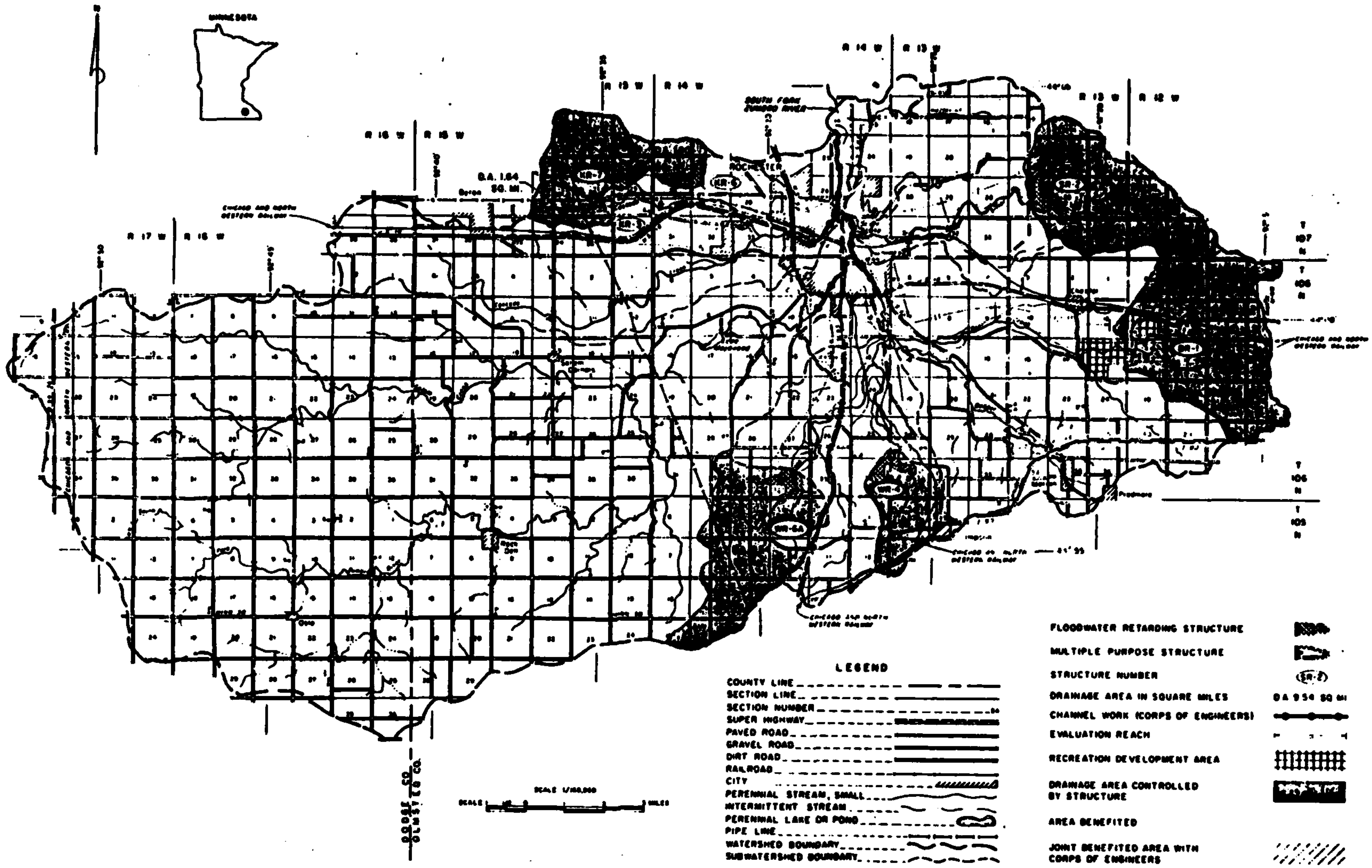


Figure 2. Reservoir locations (Weldon 1978)

Table 1

Watershed Drainage Areas and Reservoir Capacities (Weldon 1978)

		Drainage Area square miles	Capacity acre-feet
South Fork Zumbro River		304	
Bear Creek		78.2	
Reservoir BR-1		13.1	4,500
Reservoir WR-4		4.2	1,451
Reservoir WR-6A		9.5	2,436
	Total	26.8	
Cascade Creek		36.6	
Reservoir KR-3		1.6	370
Reservoir KR-6		1.6	489
Reservoir KR-7		3.8	951
	Total	7.0	
Silver Creek		17.8	
Reservoir SR-2		9.8	2,574

e. Create "hard points" in the channel to prevent head cutting, especially at bridges, cutoffs, and places where the flow approaches critical.

f. Toe protection of drop structures and any other features should be well keyed in.

g. Use of gabions for overflow sections on tieback levees should be reconsidered and be replaced with riprap (possibly grouted) because the frequency interval of the event at which the overflow sections would be used (design frequency and greater) is much higher than the useful life expectancy of the wire baskets of the gabions (5 to 20 years).

The study herein was undertaken to determine the impacts of sediment on project performance under design conditions.

Study Objectives and Approach

5. The objectives of this study are to determine the impacts of

proposed channel modifications and impoundments on the sediment transport characteristics of the South Fork Zumbro River, Cascade Creek, and Bear Creek. The analysis includes:

a. The impact of sediment scour/deposition on the water-surface elevations during floods.

b. Location and extent of scour and deposition.

c. Future dredging requirements with estimated frequency, volume, and location.

d. Recommendations on modifications to the design to reduce adverse impacts, reduce first cost, and minimize maintenance.

Study Approach

6. To accomplish the objectives, the "Network" version of the computer program, "HEC-6, Scour and Deposition in Rivers and Reservoirs," was used to model the South Fork Zumbro River and Bear and Cascade Creeks as a linked system with Silver Creek as a local inflow point. As a one-dimensional sediment transport computer code this version computes sediment transport through tributaries as well as the main stem. More detailed descriptions of the code are available in Thomas (1977a and 1977b).

Sediment Characteristics of the System

7. The southeastern part of Minnesota is characterized by rugged terrain, steep slopes, and erosive soils. Collier (1974) reported that the highest annual sediment yields in the state are in this area. Weldon (1976) computed an annual sediment yield of 185,000 tons/year or 610 tons/square mile at the USGS gage on the South Zumbro River near the Rochester water treatment plant and concluded that about 10 percent of the total sediment yield is from streambank erosion of Bear Creek and South Fork Zumbro River. Cascade and Silver Creeks are fairly stable. About one-sixth (17 percent) of the sediment yield from U. S. watersheds (Office, Chief of Engineers, 1982) is from streambank erosion as compared with 10 percent for the South Fork Zumbro watershed which implies that the streambanks in the South Fork Zumbro River watershed are more stable than the average watershed.

8. Historically, the planform geometry of the system has not changed significantly over the years as evidenced by the growth of mature trees along

the river and creek banks. These observations and paragraph 7 indicate that the high sediment yield can be attributed mostly to the erosive soils and rugged terrain with the existing channel system being fairly stable.

1978 Flood of Record

9. During the 1978 flood, the left levee of Mayowood Dam (Figure 3) was breached and flows cut into the left floodplain significantly increasing the size of an old channel extending approximately 1/2 mile downstream from the dam. Approximately 100 ft wide and 15 ft deep, this newly cut channel produced a large volume of sediment which eventually caused excessive aggradation at the upper end of the study area, especially near Apache Mall. The Zumbro River degraded almost 15 ft at the U. S. Highway 14 Bridge, started to fill back during the recession of the event, and later required further fill by local interests. Some degradation was observed on Bear Creek, however, not enough to endanger any bridges or to cause excessive bank failure. In general, the planform geometry of the system did not change.

10. After the 1978 flood, the city of Rochester dredged at the following locations.

- a. Upstream of the 2nd St. Bridge on the inside of the bend - 2,747 cu yd.
- b. North of the 12th St. S.W. Bridge (Highway 14) - 652 cu yd.
- c. North of 4th St. S.E. Bridge on Bear Creek - 643 cu yd.
- d. South of 14th St. N.W. Bridge on Cascade Creek - 1,100 cu yd.

It was hard to assess if the volumes dredged represented only that which was deposited during the 1978 flood or included material deposited prior to the 1978 flood.

Silver Lake

11. Originally constructed in 1855-1856 and reconstructed in the 1930's, Silver Lake Dam, located just upstream of North Broadway Bridge on the South Fork Zumbro River, has caused deposition in the lake such that the mean water depth of 18.3 ft in 1938 had changed to about 5 ft in 1970. The lake is periodically dredged and although accurate records are not available, 43,000 cu yd of material was removed in 1975-76 after the 1974 flood and about 30,000 cu yd

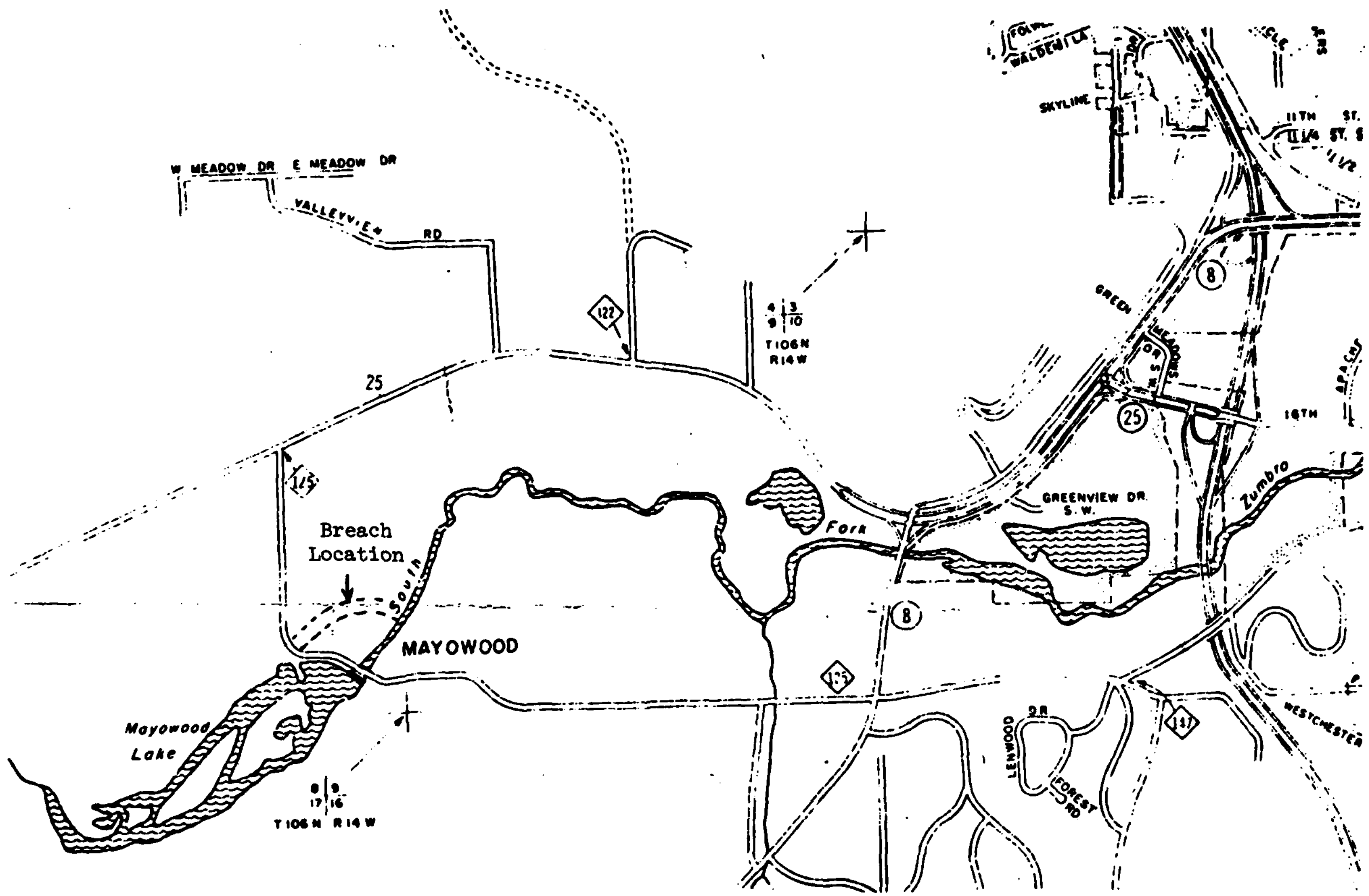


Figure 3. Location of Mayowood Dam breach

was removed after the 1978 flood. Because of the low storage capacity, Silver Lake does not help in reducing flood peaks. With such a low detention time, the lake allows most of the sediment to pass through during floods; in fact, localized scour could occur in the lake at flood peaks.

PART II: NUMERICAL MODEL DEVELOPMENT FOR EXISTING CONDITIONS

13. The term "numerical model" refers to the computer data input which contains the geometric, sediment, and hydrologic representation of the prototype. The computer code, HEC-6, utilizes these data as input to algorithms in the code that relates the data to hydraulics and sediment transport processes. The model consists of digitized representation of prototype geometry, sediment characteristics of the streambed and inflowing sediment loads, and representative historic or synthesized hydrology.

Geometric and Hydraulic Model Development

14. Calibrated HEC-2 data decks of existing and proposed condition geometry were provided by NCS along with topographic maps and aerial photographs. The existing conditions geometry represented the 1980 survey. The HEC-2 decks for both existing and proposed conditions previously had been calibrated to the 5-, 10-, 25-, 50-, 100-year frequency events along with the design and Standard Project Flood (SPF) events. These decks were modified to HEC-6 input format.

15. Because of the HEC-6 limitation of 150 cross sections and the need to keep sediment computational time to a reasonable amount, many HEC-2 cross sections were deleted. To accomplish this and yet maintain the sediment transport characteristics, the following criteria were used.

- a. If three or more consecutive cross sections were similar, the middle cross sections were deleted.
- b. A cross section was retained at each bridge and if more than one HEC-2 cross section was used to represent a bridge, only the section with the highest velocity in the channel was retained.
- c. Cross sections at confluences and those that resulted in drastic changes in hydraulic properties such as hydraulic jumps and critical flow were retained.

16. Using the above criteria, the existing conditions HEC-2 model of the South Fork Zumbro River was reduced from 125 to 60 cross sections, Cascade Creek from 83 to 31, and Bear Creek from 40 to 17, for a total of 248 HEC-2 cross sections to 108 HEC-6 cross sections. The reduction in detail is not as

drastic as it appears because bridges are represented by up to four cross sections in HEC-2 whereas HEC-6 uses only one.

17. Hydraulic calibration of HEC-6 consisted of reproducing the HEC-2 water-surface profiles calculated by NCS for the 5- and 50-year frequency events plus the design flood and the SPF. Calibration was considered acceptable when the water-surface elevations of the HEC-6 runs using the "fixed-bed" mode were within ± 0.5 ft of the HEC-2 runs.

18. Although matching water-surface profiles was the main criterion in the calibration, water velocity and flow distribution from HEC-2 runs were examined and where reasonable, used as additional criteria in the HEC-6 calibration. Some adjustments to flow distribution were required to prevent excessive overbank flows. Channel velocity was not allowed to decrease with increasing discharge.

19. In regard to channel velocities, HEC-2 has the capability of defining ineffective flow area for each discharge analyzed. In the HEC-2 calibration, NCS used this option (i.e., ET cards) to reconstitute observed water-surface profiles up to the design discharge. The field data ranged to about the design discharge and when the SPF discharge was calibrated, all the flow area was allowed to become effective causing a decrease in channel velocity for an increase in discharge. It was decided to simulate the ineffective flow area variation with discharge in HEC-6 by allowing Manning's *n* to change with elevation or discharge for the overbanks and channel. This newly developed option in HEC-6 was used to redistribute the flow so that velocities and flow distribution were reasonable over the entire range of discharges and similar to the HEC-2 results for discharges up to and including the design discharge.

20. HEC-6 does not simulate bridge loss in the manner HEC-2 does. To reconstitute HEC-2 results in HEC-6, Manning's *n* was varied by elevation for the overbanks and channel at the bridge cross section so the water-surface elevations, water velocity, and flow distribution were similar to those of the HEC-2 runs. This same technique was used to simulate Silver Lake Dam and the drop structures.

Sediment Data Development

21. The sediment parameters used and calibrated in HEC-6 are sediment

inflow rate by weight and gradation and depth of sediment material in the streambed and its gradation. River water temperatures were obtained from the city of Rochester for the South Fork Zumbro River near the Water Reclamation Plant and the average monthly temperatures for the period 1977-1980 were used.

22. Using the American Geophysical Union classification for grain sizes, the sizes from very fine sand (VFS) to very coarse gravel (VCG) (10 sizes) were used in the model. The initial inflowing sediment load curves were developed from the suspended sediment samples obtained by the USGS. Figures 4-6 show the nature of the suspended sediment load developed from these data. Because samples included silts and clays, the calibrated inflowing total sediment loads used in the model (excluding clays and silts) were estimated by analyzing the gradation of the measured load and using only the fraction of the suspended load greater than or equal to VFS. Because there were only a few samples analyzed for gradation, the gradations used in the model were developed by allowing the model to calculate an equilibrium inflowing gradation (including bed load). This was accomplished by using the initial load curve from the measurements with an estimated gradation as input to the model. An equilibrium cross section (i.e., having exhibited very little bed change over time) was examined to determine an equilibrium total load and gradation of the moving sediment as calculated by HEC-6 using the Toffaleti transport function. This gradation and load were then input to the model and the resulting load and gradation were again input to the model. This was repeated until the inflowing and outflowing load and gradations at the equilibrium cross section were very similar. This was done for a range of discharges and for South Fork Zumbro River, Cascade Creek, and Bear Creek. Calibrated load curves and gradation were then adjusted to include clays and silts and compared with the measured load curves as shown in Figures 7 and 8. This comparison could not be made for the South Fork Zumbro because the inflowing sediment load was calibrated for the upper end of the river and the measurements were at the lower end.

23. Cross sections and bed gradations were not available for Silver Creek so the method used to obtain an inflowing sediment load gradation as described in paragraph 22 could not be used. A comparison of the measured sediment loads in Figure 9 shows that Cascade Creek and Silver Creek have similar characteristics in both slope and ordinate intercept. Because of this similarity, the calibrated inflowing sediment load and gradation for Cascade Creek were also used for Silver Creek.

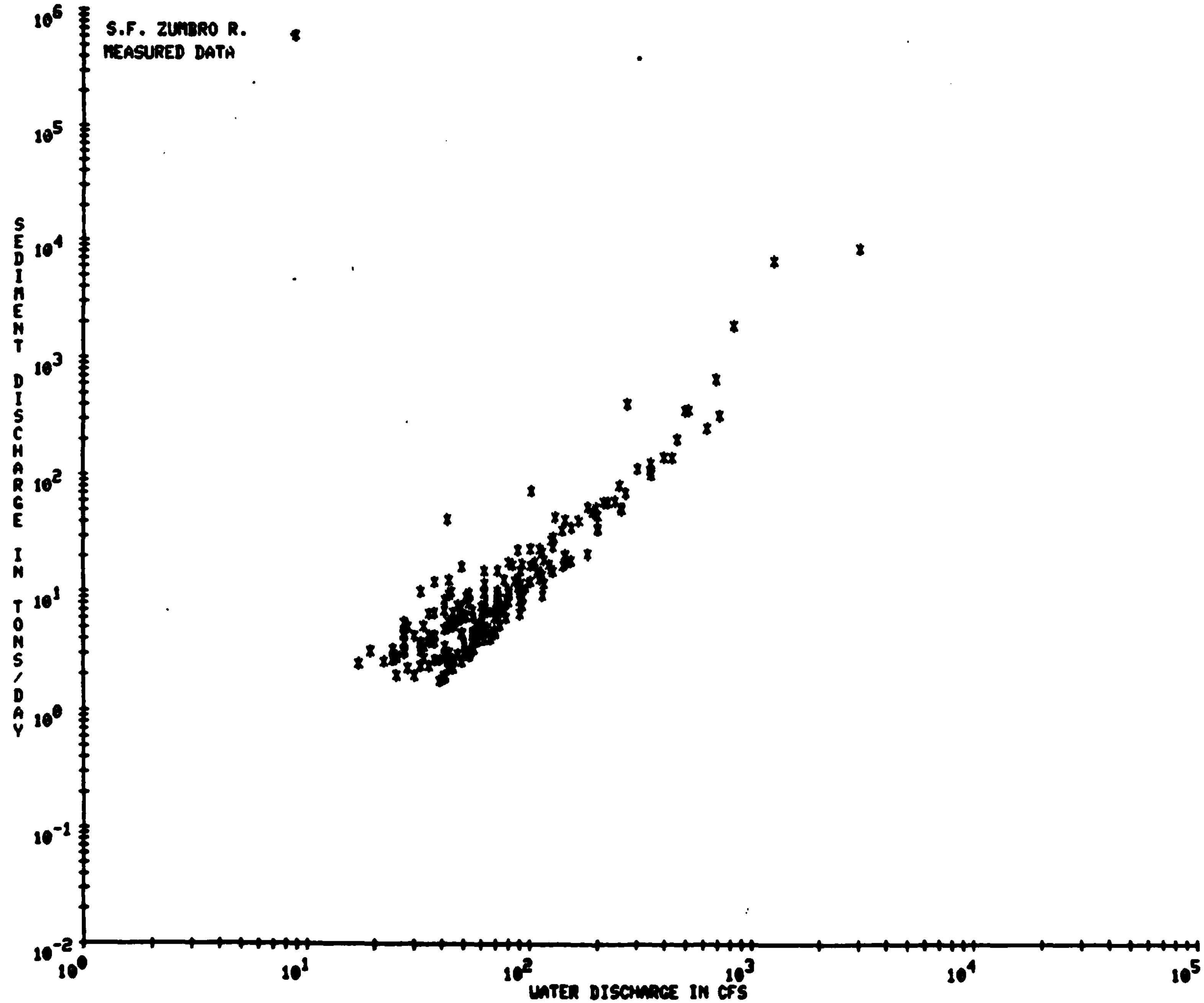


Figure 4. Suspended sediment, South Fork Zumbro River

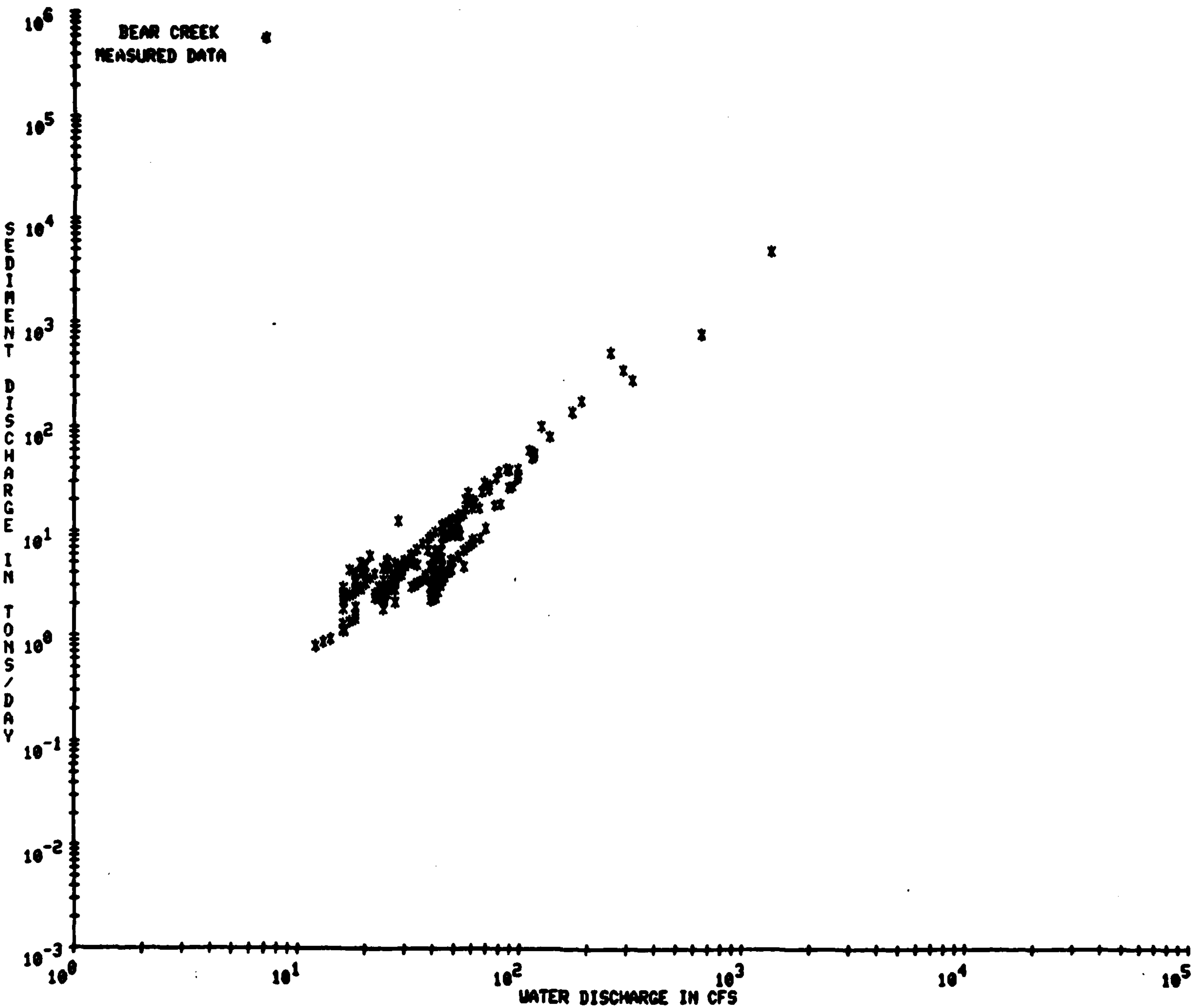


Figure 5. Suspended sediment, Bear Creek

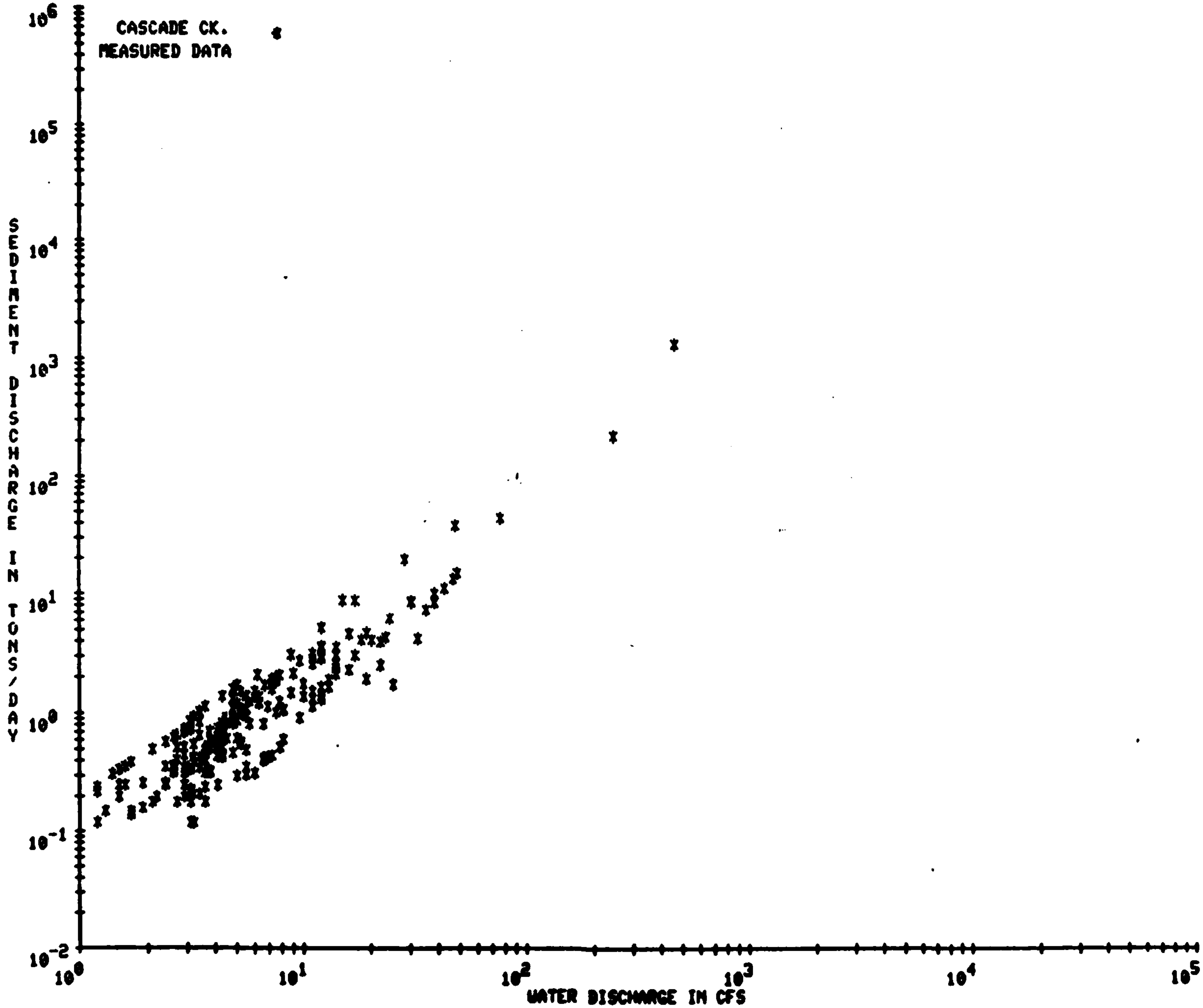


Figure 6. Suspended sediment, Cascáde Creek

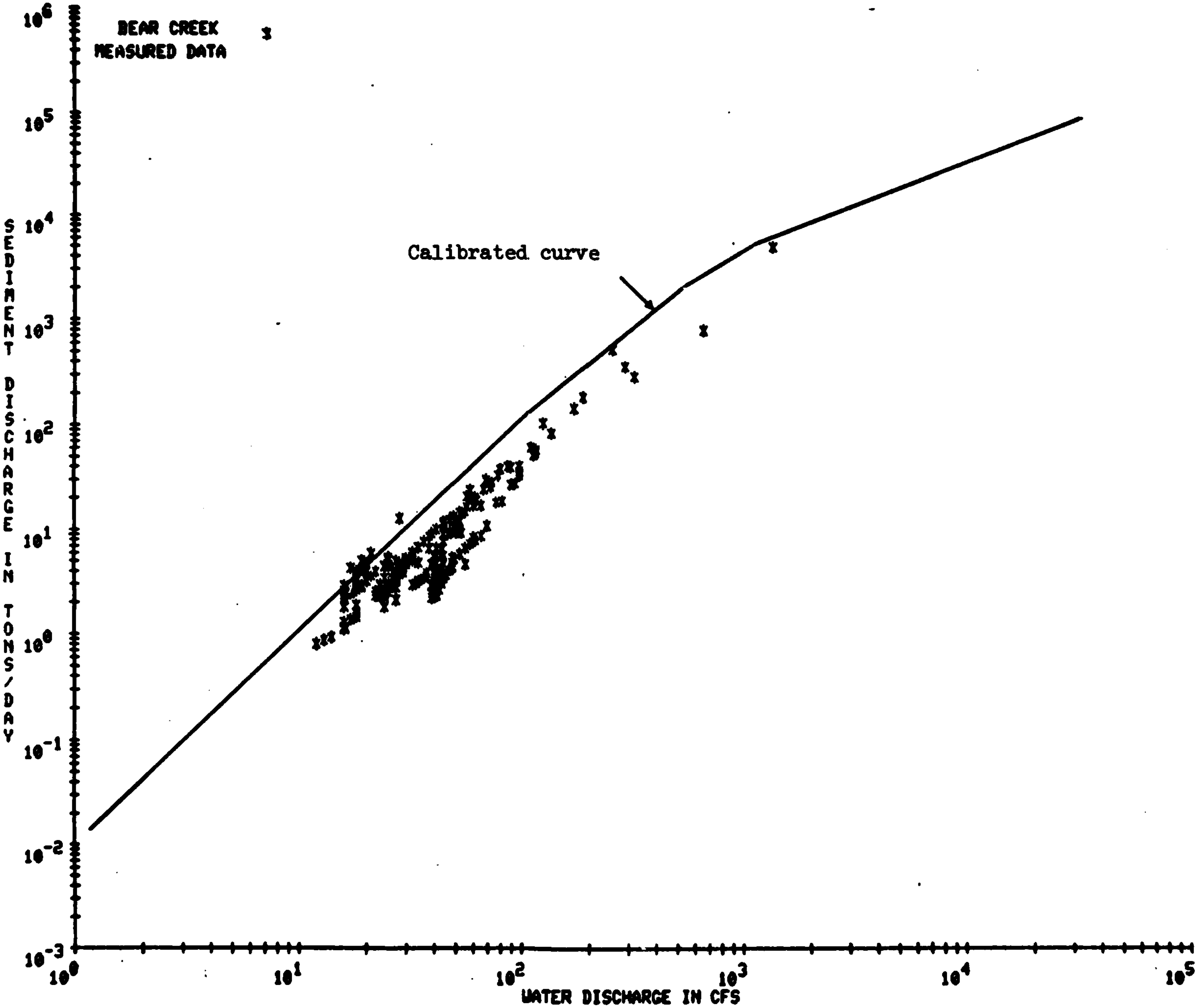


Figure 7. Comparison of calibrated and measured sediment inflow load curve, Bear Creek

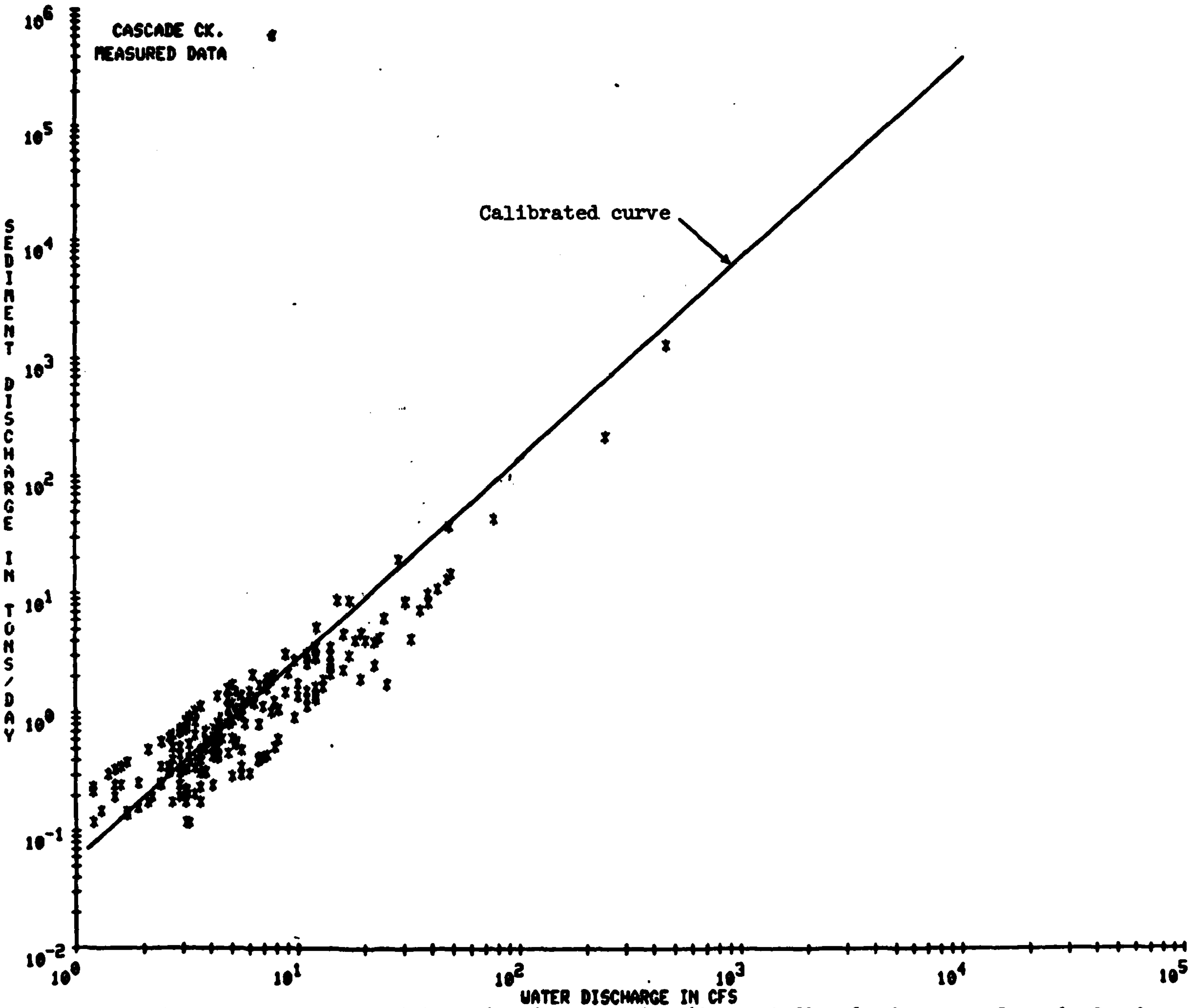


Figure 8. Comparison of calibrated and measured sediment inflow load curve, Cascade Creek

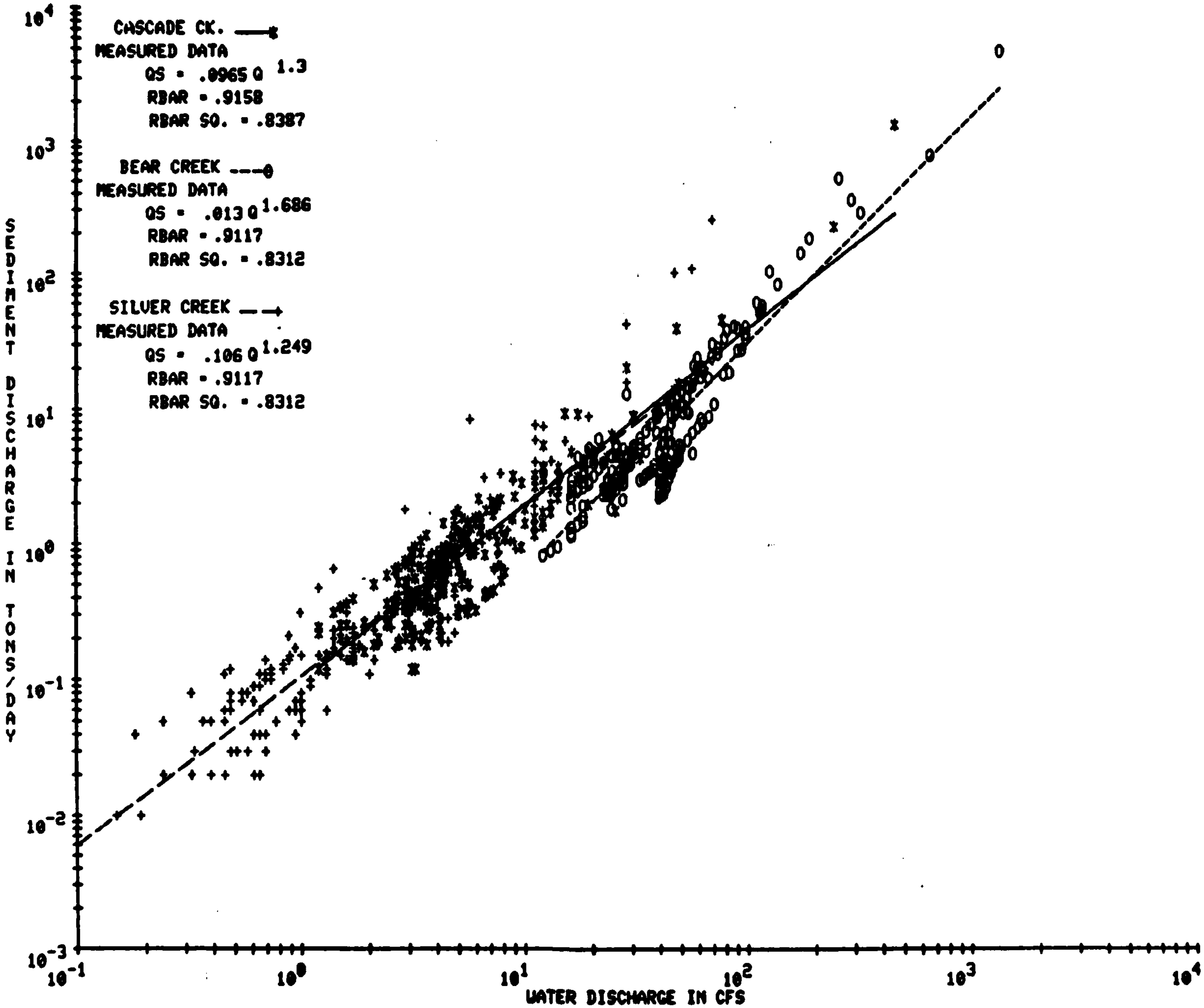


Figure 9. Comparison of measured sediment data

24. Bed gradations obtained from the field in July 1980 were used in the model. Only those gradations deemed representative of the surrounding area were used. In order to get bed gradations at cross sections where no gradations were available, a plot of bed gradation versus channel distance was constructed as shown in Figure 10. The bed gradation at any cross section can then be obtained by linear interpolation of the gradation at the channel distance corresponding to the cross section. The measured gradations for various locations on Cascade Creek were very similar; therefore one representative gradation was used as shown in Figure 11.

25. A test of the calibrated bed gradations and inflowing sediment rating curves as a linked unit was performed. This was accomplished by assuming that the existing conditions of hydraulic properties, cross-section geometry, bed gradations, and inflowing sediment load were in relative equilibrium. A series of long-term steady-state discharges were simulated and bed elevation changes were observed. The test was deemed successful because bed changes required to efficiently pass the calibrated inflowing sediment load and to reach equilibrium conditions (i.e., sediment inflow = sediment outflow) were minimal. This satisfied the conditions of the assumption.

Hydrologic Data Development

26. Thirty years (1952-1981) of mean daily discharges were available at the USGS gage. The utility program "Sediment Weighted Histogram Generator" (SWHG) was used to convert the mean daily discharges into representative histogram events for HEC-6 input. Figure 12 shows an example time period comparing the mean daily discharges (dotted line) with the histogram produced by SWHG (solid line). The use of mean daily discharges does not capture the peak discharge of significant events due to the averaging of instantaneous discharges over a 24-hr period. To correct for this, whenever an event greater than a 5-year event was encountered, the mean daily discharges representing the event were manually replaced by hourly histograms provided by NCS. The hydrographs developed by NCS showed slight unsteadiness of the system due to storage and the flow through time being greater than the time intervals of the hydrographs. For example, prototype inflow discharges of 100 cfs for the South Fork Zumbro River, Cascade, Silver, and Bear Creeks at time 10 hours did not necessarily produce 400 cfs at the downstream limit of the project. At the

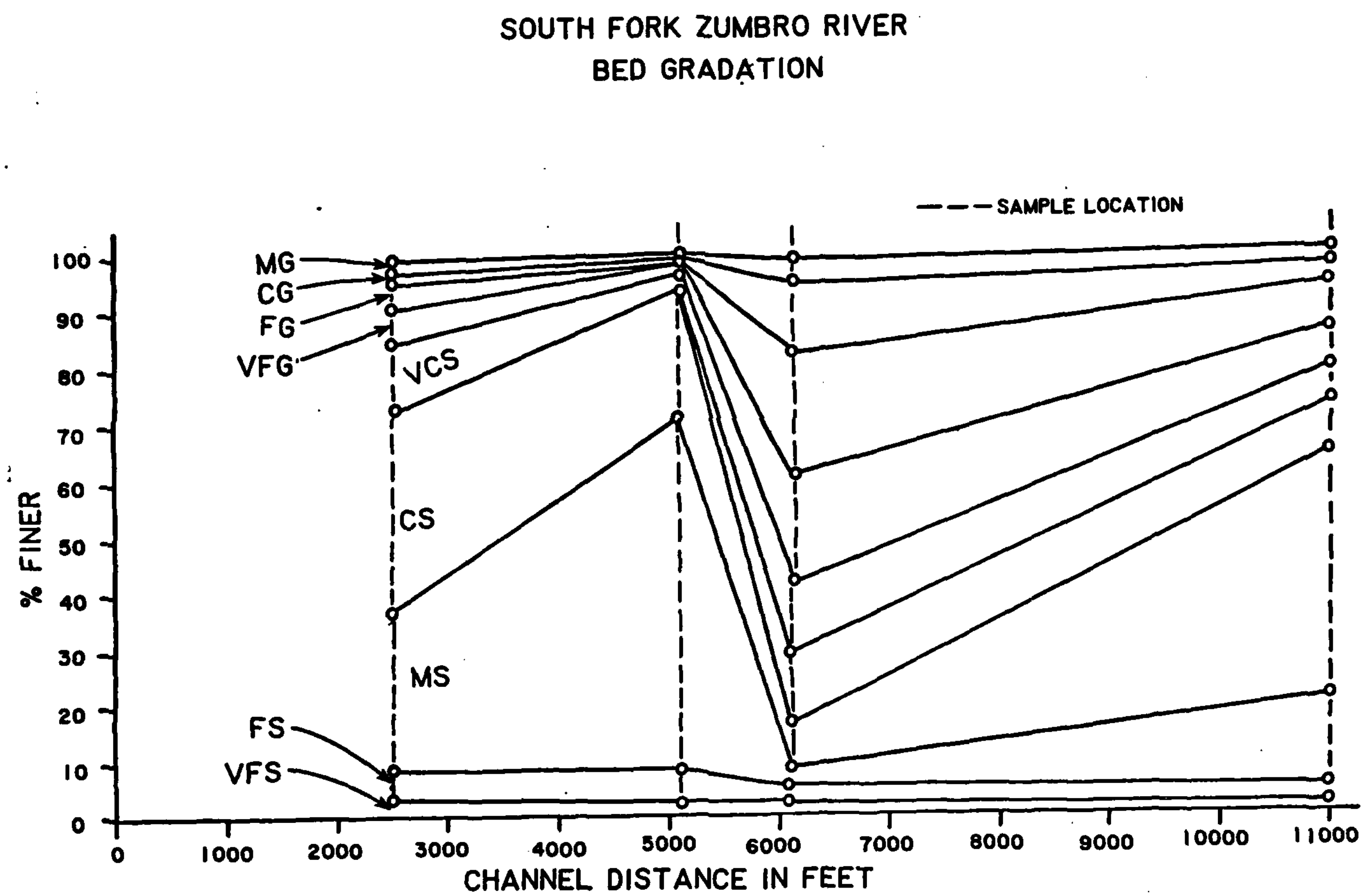


Figure 10. Example of bed gradation measurements versus distance

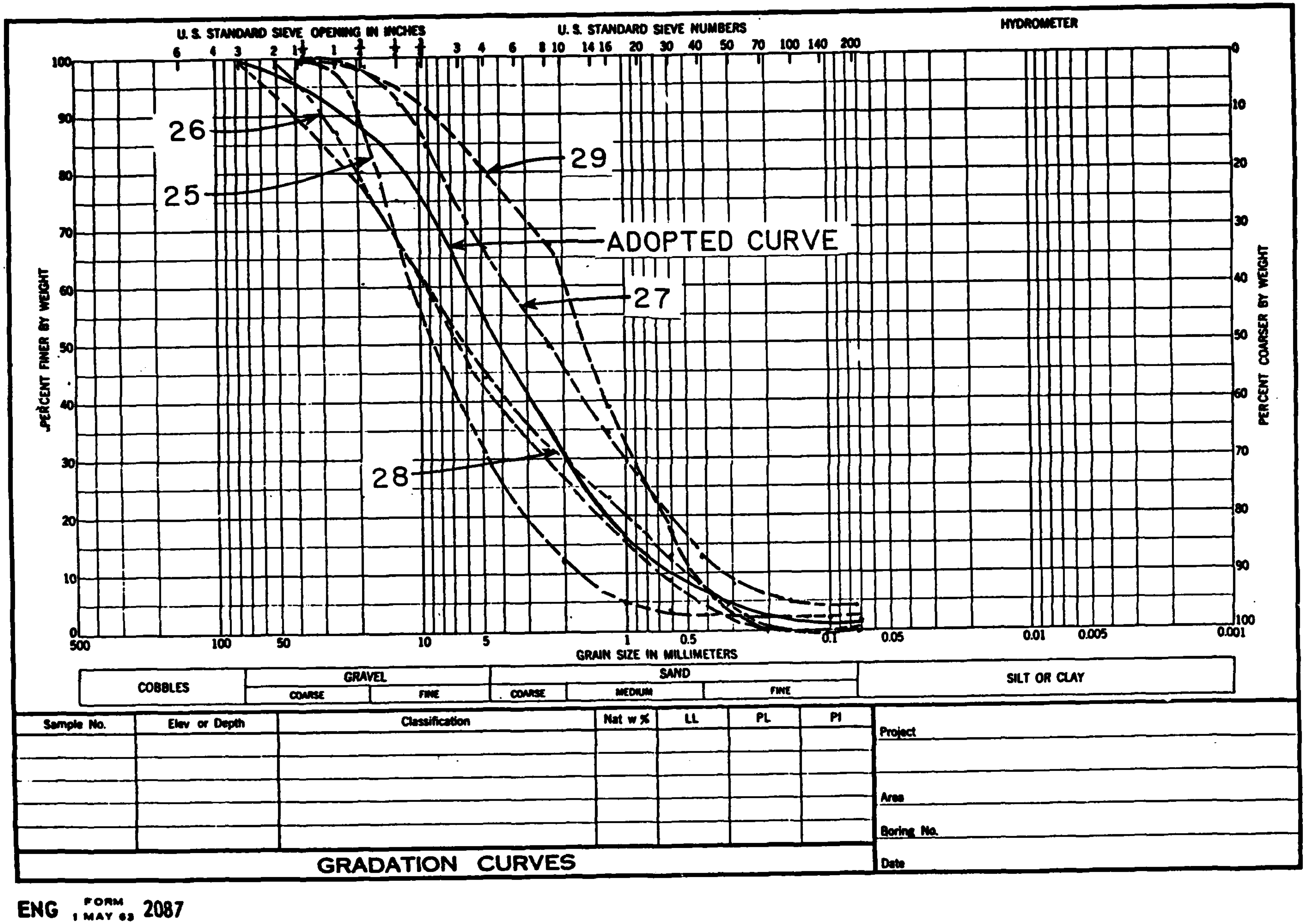


Figure 11. Bed gradations of Cascade Creek

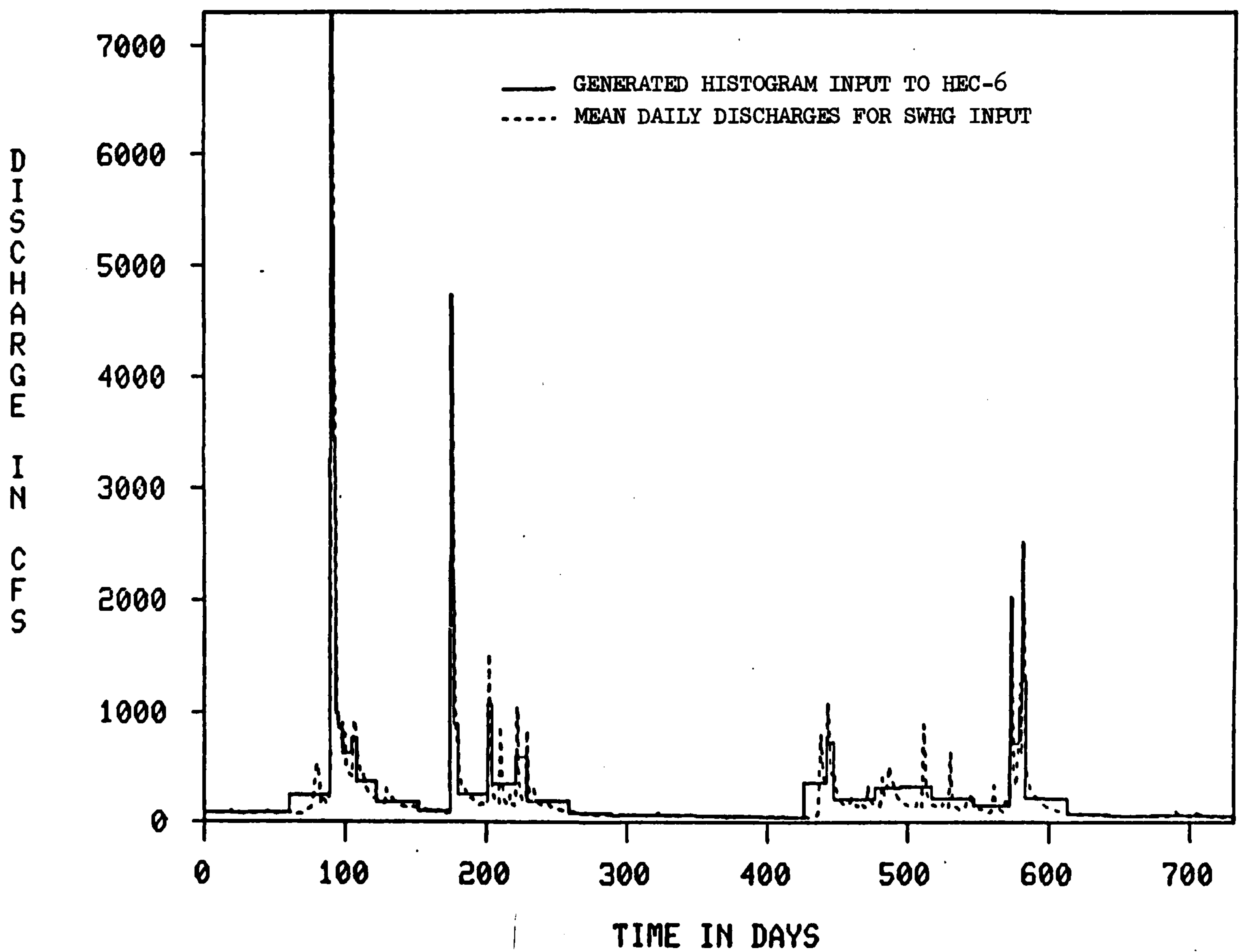


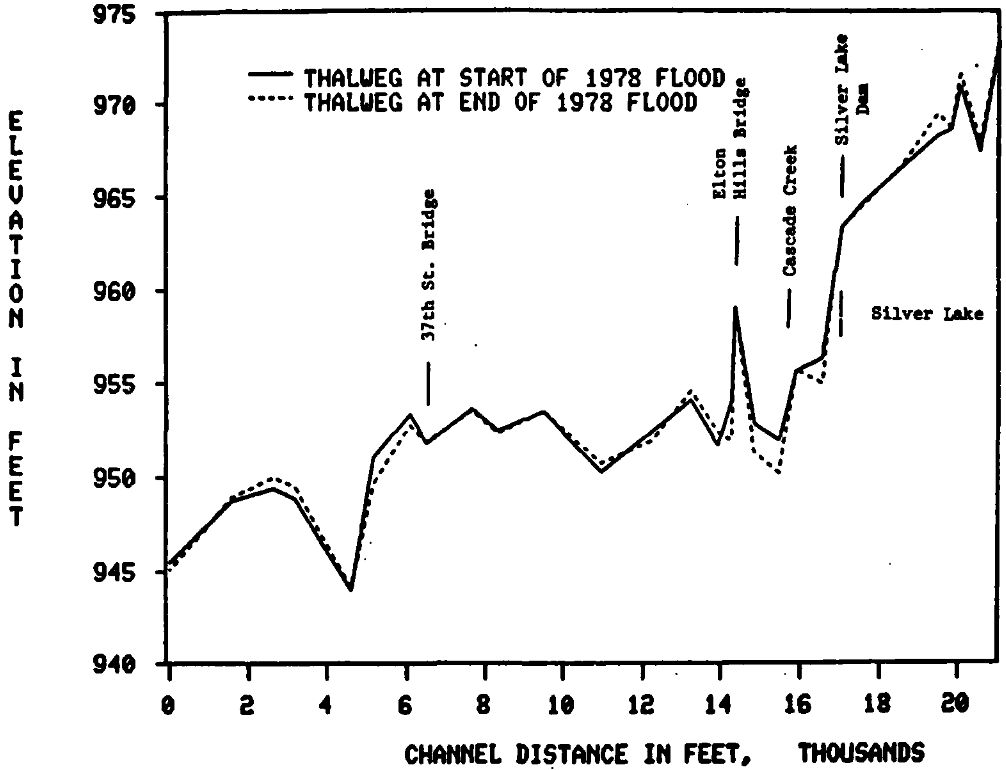
Figure 12. SWHG and HEC-6 hydrology input

beginning of an event, the discharge at the downstream limit is generally lower than the sum of the inflow discharges; and if the tributary discharges are subtracted from the downstream discharge, eventually the upstream discharge becomes negative. Because of this and since HEC-6 is a steady-state model, the hydrographs of the tributaries were slightly shifted in time in relation to the main stem. Discharges were also slightly adjusted to prevent negative flow. These adjustments did not affect the peak discharge of the tributaries nor the total volume of water of the events. The only effect of these changes on model performance is a slight shift in the water-surface elevation at the mouth of the tributaries.

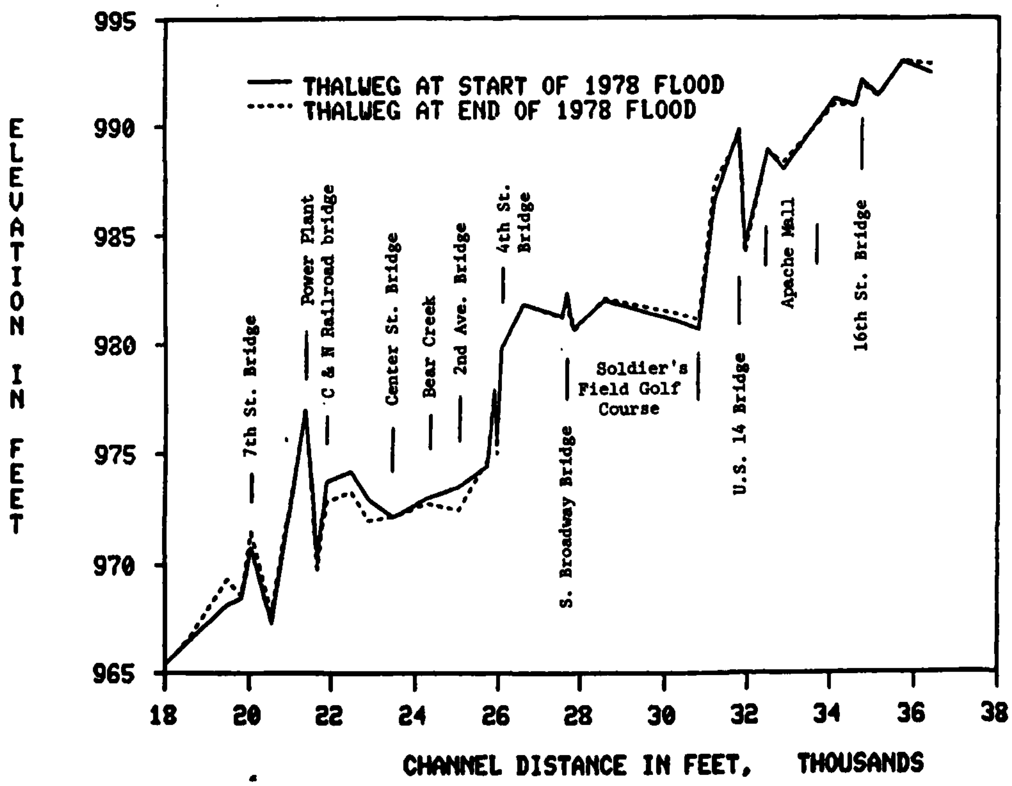
PART III: MODEL VERIFICATION

27. The traditional approach in verifying a sediment movement model is to simulate a historic sequence of discharge events and compare the bed changes of the model with the prototype bed change for the same time period. This requires successive prototype surveys. Past surveys were available; however, most of the locations did not coincide with those of successive surveys and would have required another model to be calibrated for these cross sections. Furthermore, dredging and man-made channel modifications within the verification time period were undocumented. Verification was thus limited to comparisons of bed changes of the prototype and HEC-6 model using the July 1978 event. Loss of accuracy using this verification procedure is minimal because the calibration gave very good results. The 1980 geometry was not representative of the geometry just prior to the July 1978 event. To obtain this geometry, existing conditions hydrology from 1972 to July 1978 was used and then the July 1978 flood was included. Comparisons were made based upon the geometry conditions just prior to and after the flood.

28. Unfortunately, there were no prototype surveys of bed conditions immediately before or after the July 1978 event. However, based on information provided by NCS, some general scour and deposition patterns are known. On the South Fork Zumbro River, the July 1978 flood caused deposition at the Soldier's Field Golf Course, near the 16th St. Bridge, Apache Mall, and at Silver Lake. Scour was observed at the U. S. Highway 14 Bridge and downstream of the 37th Street Bridge. Figures 13a and 13b show the calculated bed profile from HEC-6 for the South Fork Zumbro River after the 1978 flood. The figures show deposition in the upstream extreme of Soldier's Field Golf Course and near the backwater area of Silver Lake Dam. Scour is shown downstream of the Center Street, South Broadway, 2nd Avenue, and 37th Street Bridges, and slight scour near the U. S. Highway 14 Bridge. Although scour could not be field-observed because of murky water, high-water velocities were observed near the Center Street Bridge and downstream of the South Broadway Bridge, which suggests scour could have been likely at these places. The model showed only slight deposition near Apache Mall, but the observed significant deposition in the prototype was probably from the unusually high sediment discharge caused by the breach and new channel cut downstream of Mayowood Dam. That process was not included in the study. The model results showed less scour than was



a



b

Figure 13. South Fork Zumbro River, existing condition

observed at the 14th Street Bridge. Scour occurred under abutments and piers which indicates local scour occurred involving a flow phenomenon which HEC-6 does not simulate, thereby causing the model to underestimate scour. This does not pose a problem for the analysis of proposed conditions because the design includes substantial scour protection at all the bridges. Bed elevation changes predicted in the model may not appear to be as large as those seen in the prototype because HEC-6 distributes the volume of sediment scoured or deposited over the entire wetted perimeter. An observer may see a 5-ft-high sandbar which, if distributed over the entire channel, would be deposition of significantly less height.

29. Figure 14 shows the results of the simulation of the 1978 flood for Bear Creek. HEC-6 calculated only minor changes primarily due to the bedrock outcrop which predominates the streambed. Scour is shown downstream of the 4th Street Bridge and although no direct observations of scour were possible in the prototype, high velocities were observed at that location during the 1978 flood.

30. Figure 15 shows the results of the simulation of the 1978 flood for Cascade Creek. About 1,100 cu yd of sediment was dredged from the area downstream of 14th St. N.W. Bridge after the flood. There were no indications that this volume was entirely from the flood; however, the model did show a slight deposition trend in this area but not to the extent expected.

31. Silver Lake was dredged in 1975-1976 and 30,000 cu yd was dredged after the 1978 flood. This compares favorably with the HEC-6 simulation of that flood in which 23,500 cu yd of deposition was calculated. This assumes that silt and clay do not deposit in appreciable amounts in Silver Lake, which is supported by the gradation of the dredged material in that only 2 percent is finer than sands. The difference between the amount dredged in the prototype and deposited in the model can be attributed to the fact that some of the material in the prototype deposited before the 1978 flood event, whereas the model only simulated the 1978 flood. Also, the actual dredging template was not documented; therefore it is difficult to assess if the dredging limits were comparable to the 1980 geometry after it was changed by the 1972-1978 hydrology.

32. A 6.5-year simulation of the existing conditions hydrology for 1972-1978 resulted in an average annual sediment yield of 6,500 tons for sands and gravels at the USGS gage. The USGS calculated a total annual load of

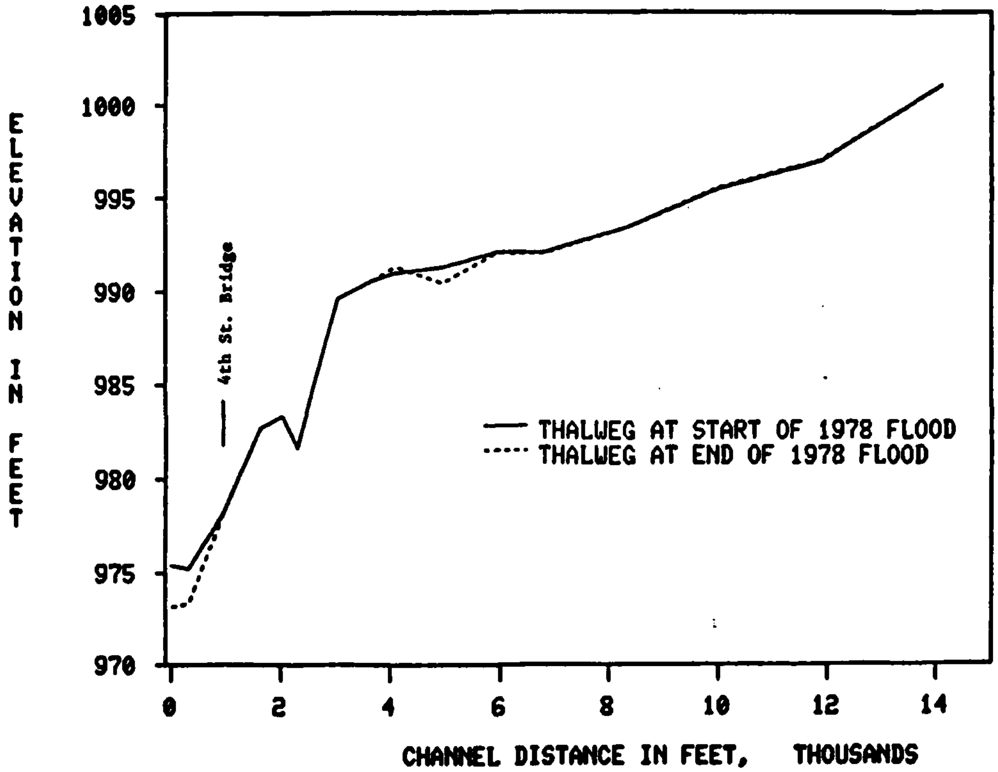


Figure 14. Bear Creek, existing conditions

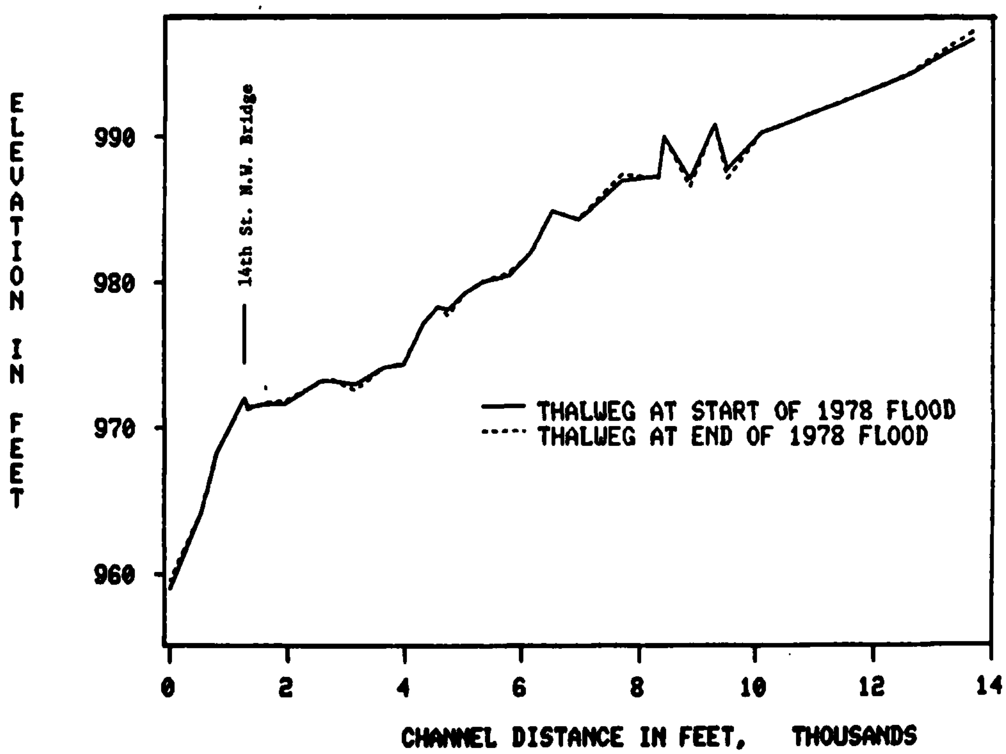


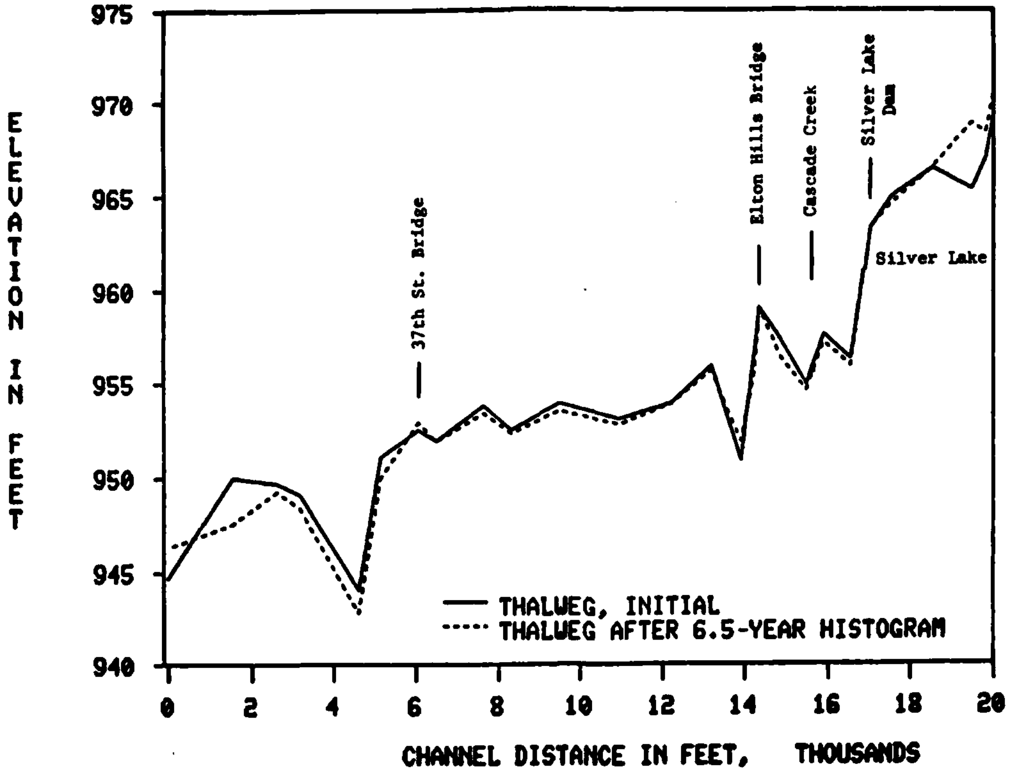
Figure 15. Cascade Creek, existing conditions

40,000 tons/year using the suspended sediment data collected for the years 1980 and 1981, which was considered to be indicative of the long-term average. For the coarse load of 6,500 tons/year to be representative of a total load of 40,000 tons/year, the percentage consisting of fine sediments (i.e., less than 0.062 mm) would have to be 84 percent. A measurement at the treatment plant on the South Fork Zumbro River showed that 79 percent of the total load consisted of sediment finer than 0.062 mm. Using field data, the USGS made eight modified Einstein computations and found that the load for sediment sizes less than 0.062 mm ranged from 65 percent to 99 percent. The sediment volume rate of 6,500 tons/year used in the existing conditions analysis appears representative of average conditions based on these comparisons. Weldon (1976) calculated an average annual sediment yield of 185,000 tons/year based upon the Universal Soil Loss Equation (USLE). The USLE was developed for small agricultural plots and the larger the drainage area, the larger the potential error in sediment yield determinations. This and the objectiveness of the parameters in the USLE could account for the difference.

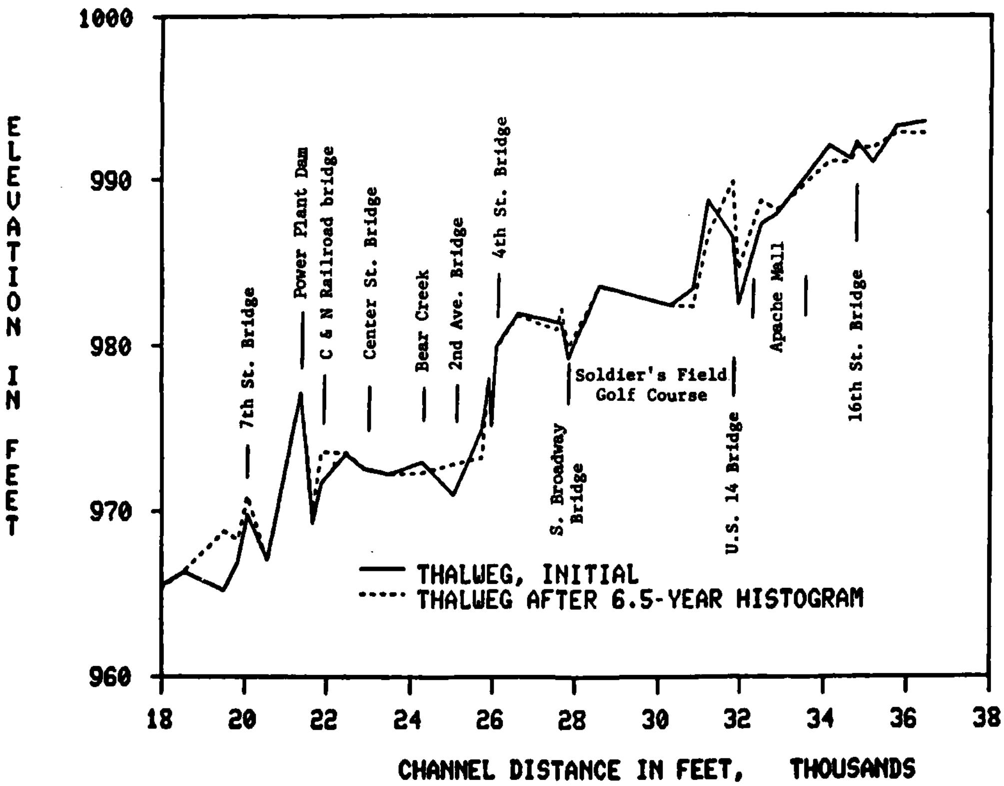
33. The hydrologic sequence used in the base test (described later) and analysis of the proposed condition consisted of a "warm-up" discharge, the design event, and the 1972-1978 (6.5 years) histogram. The base test used existing conditions hydrology, and excluding the warm-up discharge, the total volume of water used for the simulation matched the volume at the USGS gage within ± 5 percent error. This analysis could not be made for the proposed condition because the modified condition hydrology cannot be compared with existing conditions hydrology.

PART IV: BASE TEST

34. The base test is the simulation of the existing condition with which the design condition is compared. The hydrology of the base test consisted of a warm-up discharge for 50 days, the design event under existing conditions, and the 1972-1978 histogram with hourly hydrographs inserted for events greater than the 5-year event. This sequence is also used for the design condition analysis. Figures 16-18 show the initial and after simulation thalweg profiles. This is a hypothetical projection of what the system would be like 6.5 years after the 1978 flood if there is no project. The results for the South Fork Zumbro River show deposition at the Apache Mall area and U. S. Highway 14 Bridge, degrading trends between the Soldier's Field Golf Course and U. S. Highway 14 Bridge, deposition near the lower end of the Soldier's Field Golf Course, deposition at the 2nd Avenue Bridge and the C&N Railroad bridge, significant deposition at the 7th St. Bridge and Silver Lake, and slight degradation downstream and upstream of the 37th Street Bridge and near the vicinity of the confluence with Cascade Creek. Bear Creek showed scour near the confluence with the South Fork Zumbro River during the design event, but the subsequent 6.5-year histogram partially filled the area showing a tendency toward the initial thalweg. The upper half of Bear Creek showed a fairly uniform deposition of about 0.5 ft. Cascade Creek showed little activity except for a scour tendency near Kutsky Park. This could be attributed to the use of an average bed gradation in the model of Cascade Creek, whereas the prototype probably had a coarser bed gradation because of the narrower cross sections in this area. The base test resulted in 8,900 cu yd/yr of sands and coarser being deposited in Silver Lake. Calculations for the 1972-1978 period produced 18 percent higher annual sediment yield than the long-term period of 1952-1981. This implies that the base test results of 8,900 cu yd/yr is probably higher than the long-term average and should be reduced by 18 percent to 7,300 cu yd/yr. This value is comparable to the dredged amounts of 5,000 to 10,000 cu yd/yr estimated by the city of Rochester (Ames 1975) and 12,700 cu yd/yr documented by the SCS in 1970 (U. S. Army Engineer District, St. Paul, 1982). The base test results were reasonable and are realistic when compared with expected and observed prototype behavior.



a



b

Figure 16. South Fork Zumbro River, base test, existing conditions

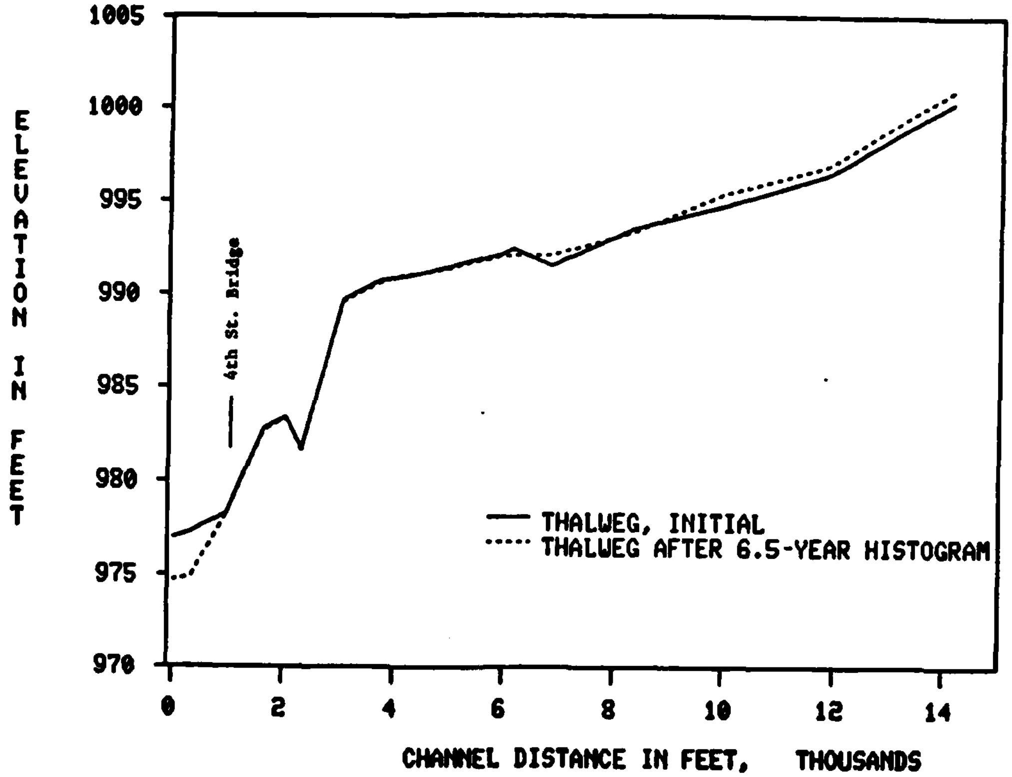


Figure 17. Bear Creek, base test, existing conditions

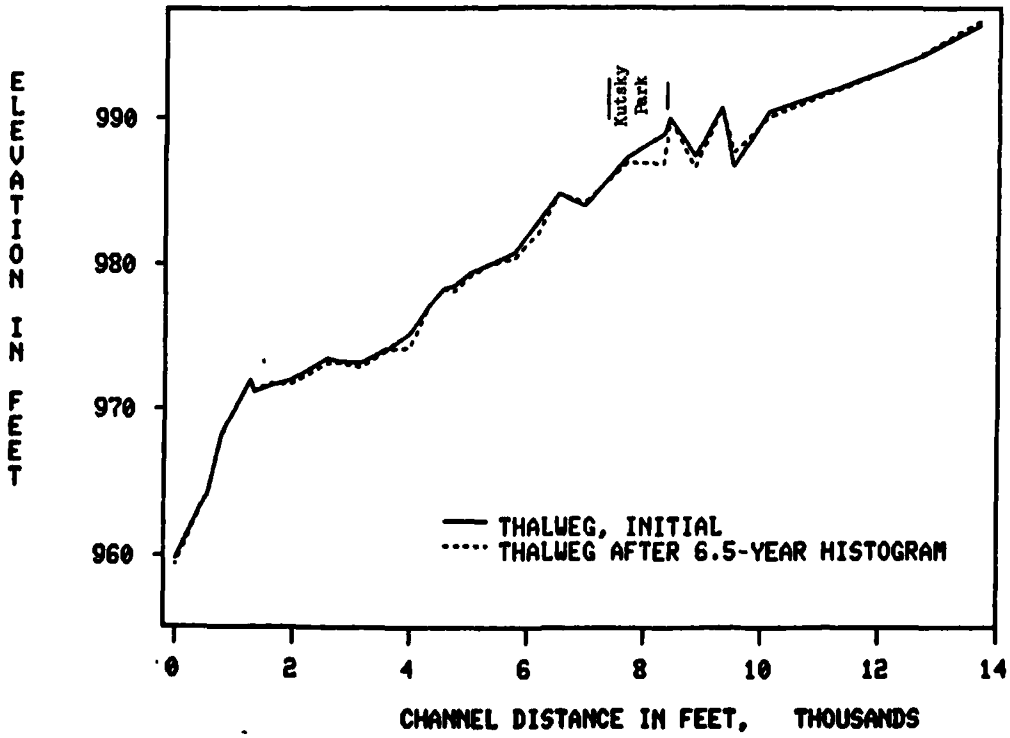


Figure 18. Cascade Creek, base test, existing conditions

PART V: DESIGN CONDITIONS MODEL CALIBRATION

Hydraulic Calibration

35. The criteria and procedures used in the hydraulic calibration of HEC-6 for proposed design conditions were the same as those used in the existing conditions hydraulic calibration except that the design geometry, hydrology, and HEC-2 water-surface profiles were used.

Sediment Data Calibration

36. The bed gradations from the existing conditions calibration were used in the design conditions model. This was considered valid because no sediment material except riprap is to be placed in the streambed from outside sources. Where the proposed design shows riprap, the cross sections were not allowed to erode in the HEC-6 model. Although the bed gradations used in the model were obtained within a few feet of the surface, they are assumed to apply to the entire depth of sediment below the streambed and NCS must be careful to assure that excavation for the design channel does not expose sand layers where the existing channel has a protective gravel surface.

37. The inflowing sediment load curves calibrated for the existing conditions were adjusted for the proposed conditions to simulate the effects of the SCS reservoirs and proposed land treatment on sediment yield. Weldon (1976) calculated existing and proposed conditions sediment yield for each subbasin. The ordinates of each inflowing sediment load curve were reduced by the percent reduction in sediment yield for the contributing watershed. Table 2 shows the results of these calculations. Although Weldon's annual sediment yield of 185,000 tons/year did not agree with the yield of 40,000 tons/year calculated by the USGS using field data, it was felt that the use of the USLE to determine percentage reduction due to reservoirs and land treatment was a realistic approach. Recognizing that the deficient sediment load could be replenished from the bed, it was assumed that the distances from the reservoirs and/or land treatment to the project limits were too short for a significant sediment load adjustment to occur.

Table 2

Reduction of Sediment Yield Under

Proposed Conditions, Unadjusted to Outlet (Weldon 1976)*

	Present Yield tons/year	Proposed Reduction tons/year	Percent Reduction
Silver Creek	16,930	9,879	58
Bear Creek	75,068	34,080	45
Cascade Creek	32,170	9,748	30
South Fork Zumbro River**	123,009	18,452	15

* Weldon used these figures and adjusted by ratio of drainage area method to determine sediment yield at the outlet (USGS gage) of the South Fork Zumbro watershed.

** Does not include Silver, Bear, or Cascade Creek.

PART VI: ANALYSIS OF PROPOSED CONDITIONS

Complete Proposed Condition

38. The model of the proposed condition consisted of the hydraulically calibrated proposed condition geometry, calibrated existing condition bed gradations, calibrated inflowing sediment load curves adjusted as described in paragraph 37, scour prevention at all cross sections with riprap or gabions in the design, and hydrology input as described in paragraph 34 but using proposed condition hydrology.

39. Both Cascade and Bear Creeks exhibited very little sediment activity and therefore results are not shown. This implies that these creeks, under proposed conditions, are generally sediment-starved or near equilibrium but cannot obtain material from the bed or banks because of the channel protection. This also indicates that little, if any, channel maintenance dredging would be required. Problems, if at all, would be erosional rather than depositional.

40. The results for the South Fork Zumbro River, Figures 19a and 19b, show scour from the 4th St. Bridge to the C&N Railroad bridge. The base test showed slight deposition in this vicinity suggesting that the scour is due to the design. This is brought out by Figure 20 which shows a higher water velocity for the same discharge for the design condition than for the existing condition. The scour will continue until equilibrium is attained, which would occur between 5 and 10 years, and produce 42,000 cu yd of sediment of which 75 percent would deposit in Silver Lake. This area is where there are existing and proposed floodwalls; therefore the streambanks are protected. The scour does not adversely affect the design water-surface elevation for the design event and the extent of further scour is limited due to the bedrock just a few feet under the streambed. NCS should assure that these existing and proposed floodwalls extend down to and are keyed into the bedrock.

41. Deposition of 2,700 cu yd/yr will occur between Silver Lake Dam and the Elton Hills Bridge while the base test shows slight scour. Examination of the proposed cross sections revealed widening of the existing geometry as typified in Figure 21 and a comparison of water velocities for existing and proposed conditions shows a general decrease of the velocity for the design condition as exhibited in Figure 22. Minor maintenance dredging will probably be required in that reach; however, the deposition does not significantly

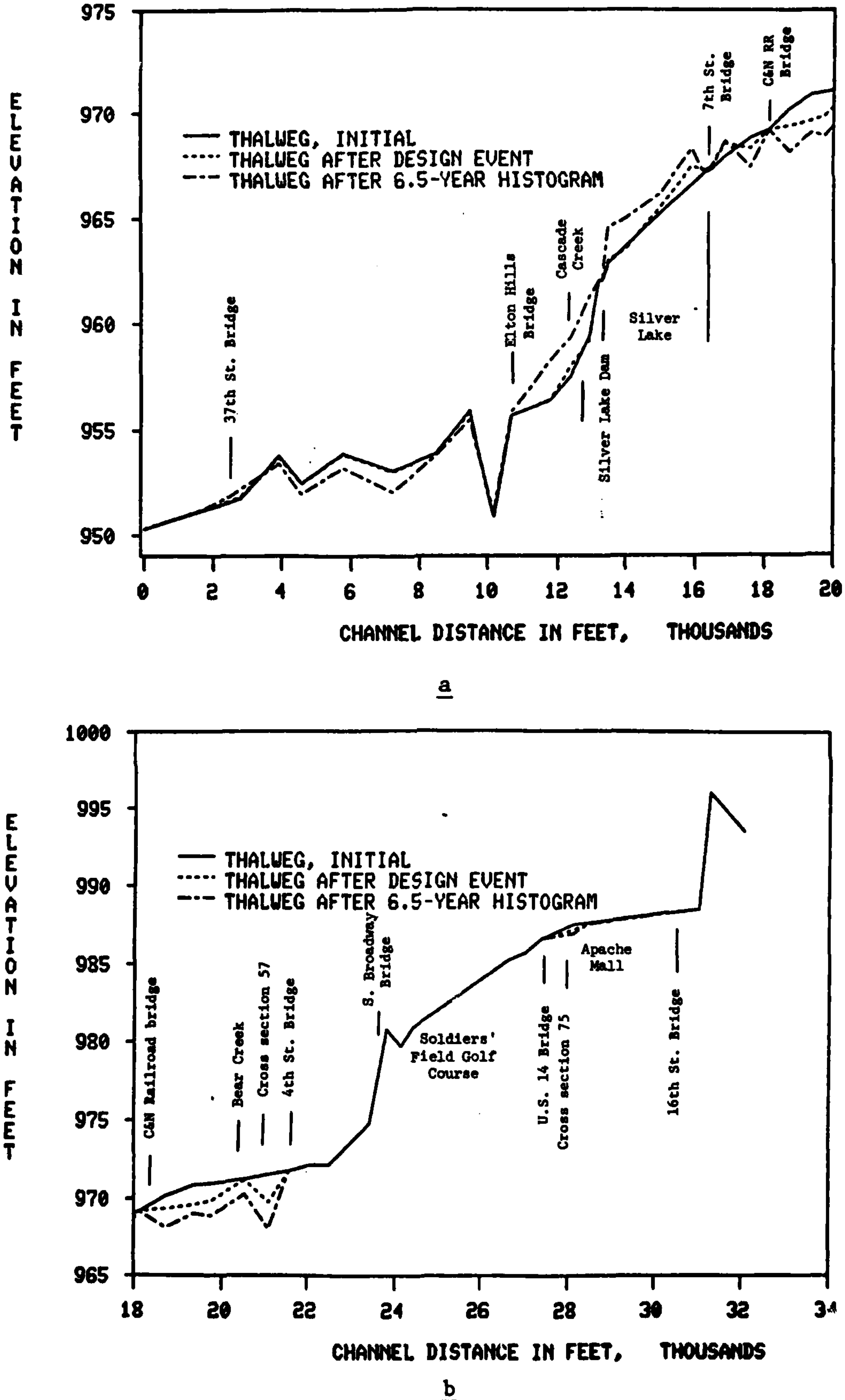


Figure 19. South Fork Zumbro River, proposed conditions

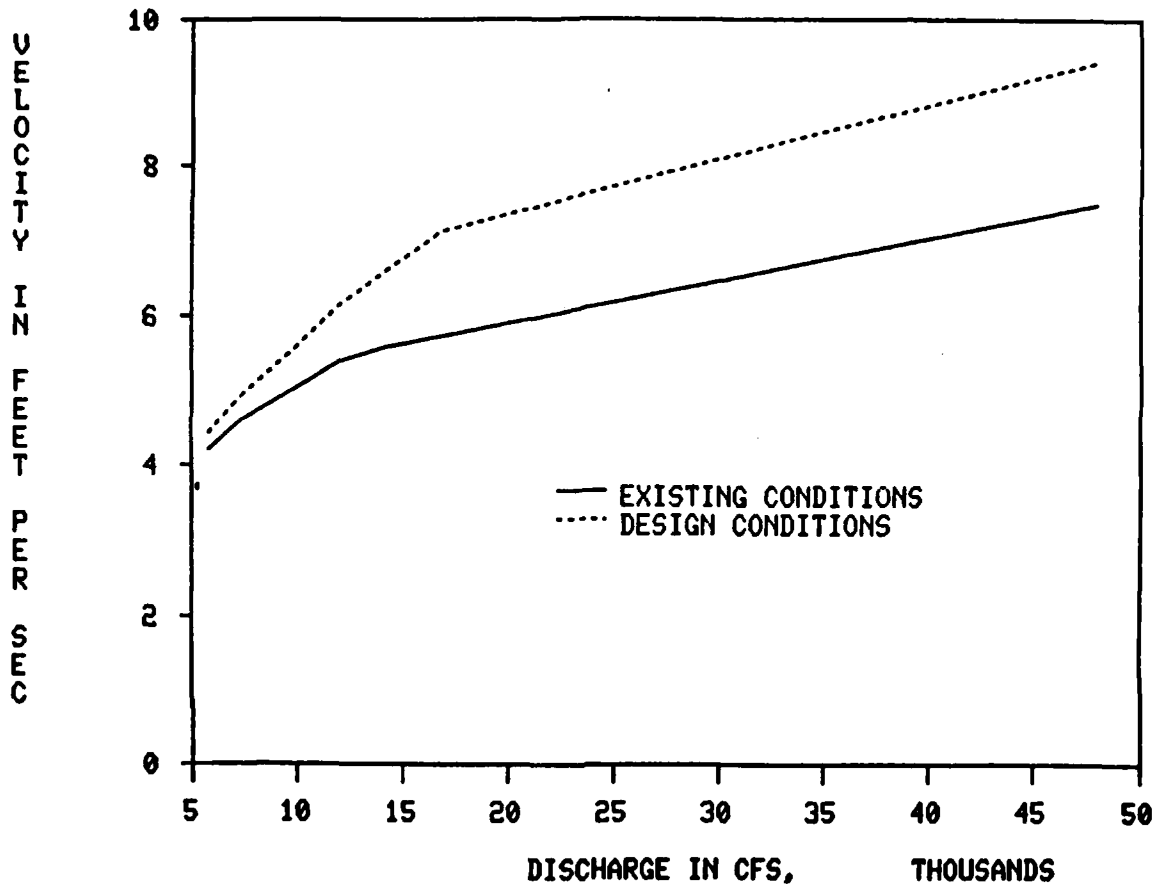


Figure 20. Section 57, comparison of existing and design water velocities

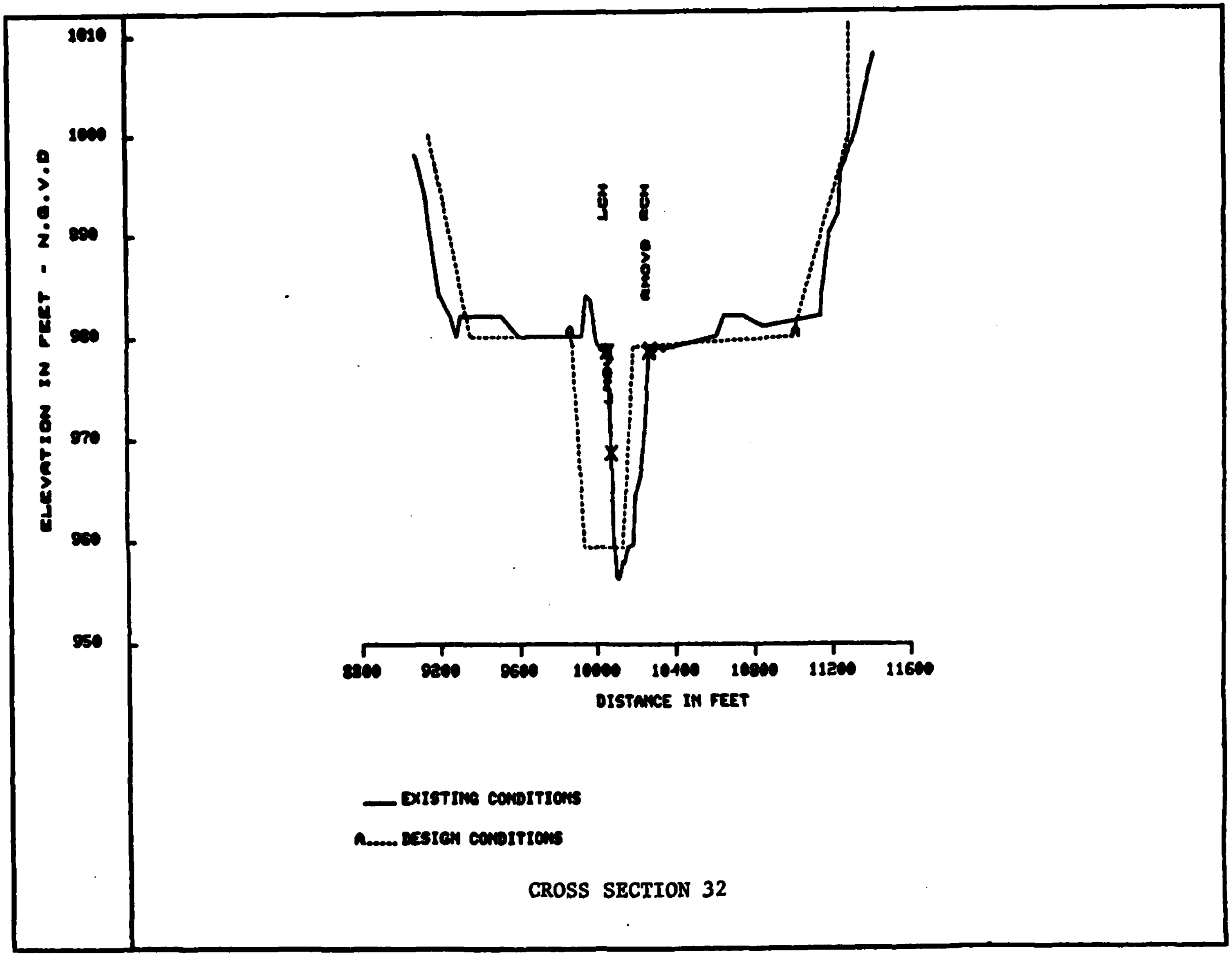


Figure 21. Geometry of channel downstream of Silver Lake Dam

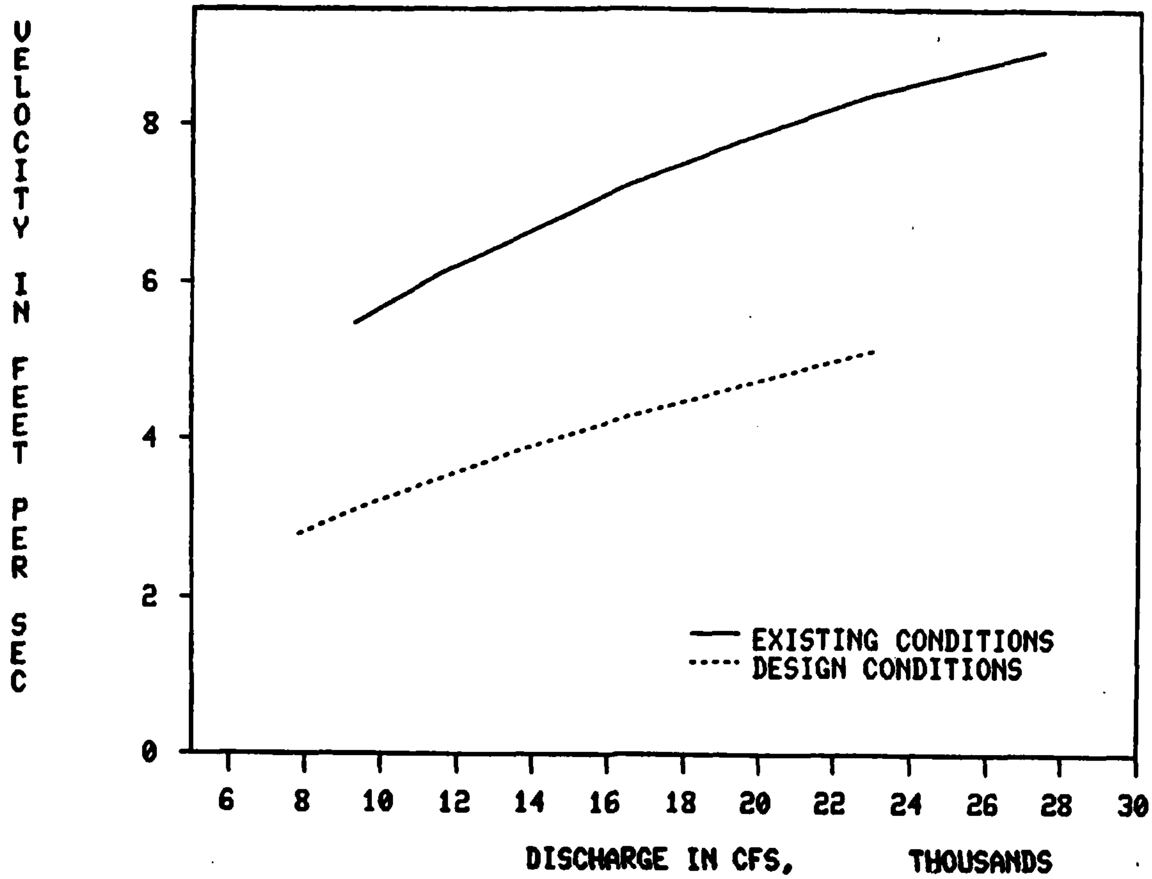


Figure 22. Section 29, comparison of existing and design water velocities

affect the design water-surface elevations during the 6.5-year simulation time period.

42. NCS had concern over the ability of the Apache Mall area to transport the inflowing sediment for the proposed condition. The model results showed no deposition in this area. This can be attributed to the low-flow channel in this area as demonstrated in Figure 23. The water stays within the channel limits up to and including the design discharge and though the sediment may deposit under extreme low-flow conditions, it would be reentrained at moderate flows which produce channel velocities greater than 3 fps. For this phenomenon to occur, local interests must ensure that significant vegetation does not establish in the channel.

43. Minor scour was calculated between Elton Hills Bridge and the 37th St. Bridge, but it was on the order observed in the base test and therefore considered insignificant.

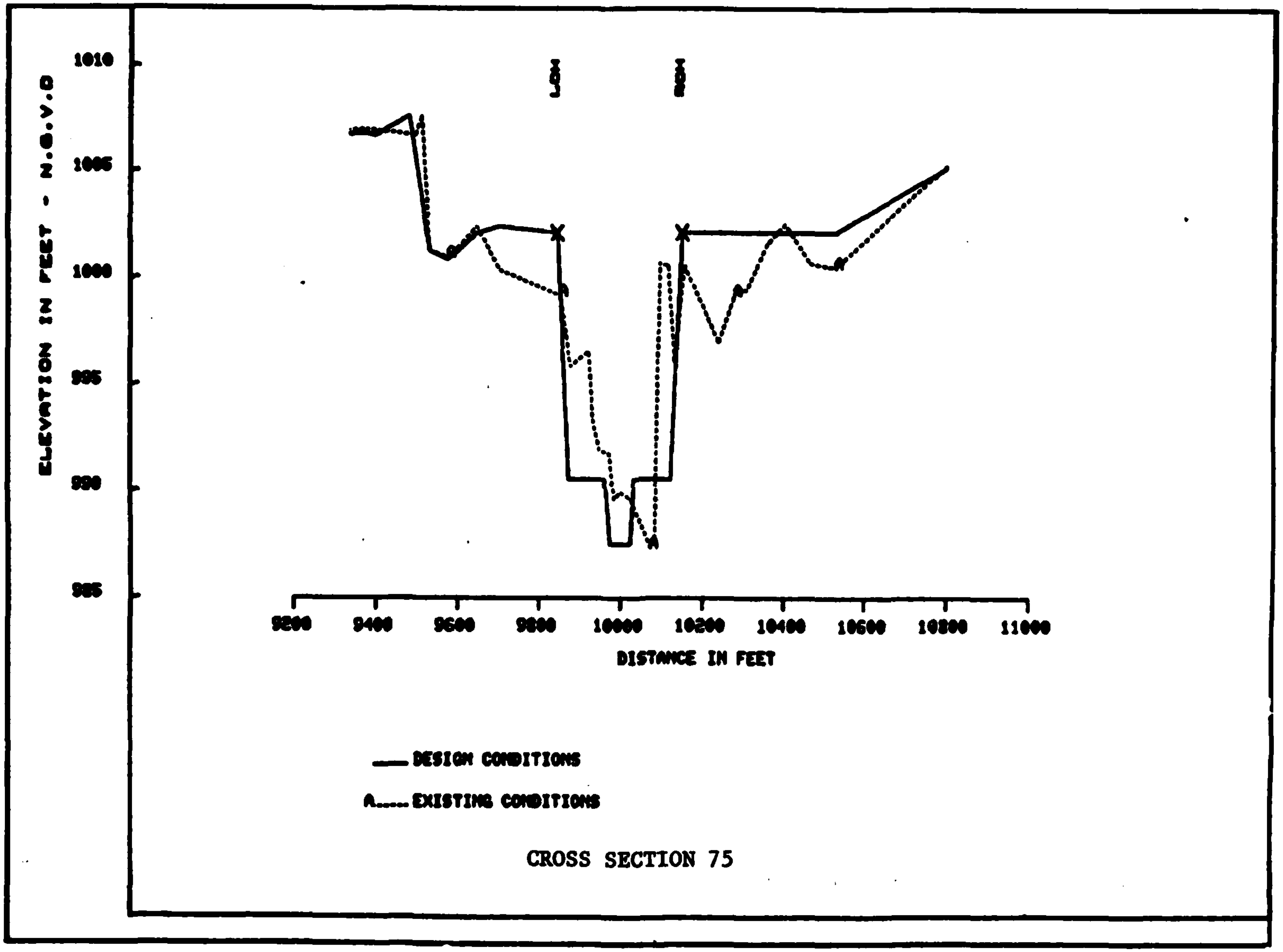


Figure 23. Geometry of low-flow channel

44. A simulation was made in which the design event was placed after the 6.5-year histogram instead of before it as previously described. No significant shifting of discharge-elevation rating curves was observed anywhere in the project which demonstrates that the project can maintain the design water-surface profiles if the design event should occur either immediately after construction or 6.5 years after construction.

Silver Lake

45. The long-term deposition rate in Silver Lake is difficult to analyze because of continuing adjustment of the river to its new geometry. As mentioned in paragraph 40, 42,000 cu yd of sediment will be scoured from the 4th St. Bridge to C&N Railroad bridge with most of it depositing in Silver Lake. If this material is included in the analysis, the present annual deposition rate of 7,300 cu yd would increase to 10,300 cu yd for 5 to 10 years. After the upstream reach achieves equilibrium, the deposition rate would fall to 1,900 cu yd/yr. If the upstream reach is protected from scour or is adjusted to its equilibrium geometry (i.e., removing 42,000 cu yd during project construction), the average annual deposition rate in Silver Lake would be 1,900 cu yd as compared with 7,300 cu yd/year for existing conditions. The lower deposition rate is due to the lowering of the elevation-discharge rating curve at the dam, better hydraulic characteristics of the lake, and reduction of the inflowing sediment load due to proposed land treatment and SCS reservoirs in the watershed. The distribution of deposits in Silver Lake will change as shown in Figure 24 with the sediment being deposited farther into the lake. Figure 24 represents conditions if the 42,000 cu yd from the 4th St. Bridge to the C&N Railroad bridge is not available for scour.

Downstream Sediment Load Rate

46. The overall reduction of the inflowing sediment loads due to modified hydrology, proposed reservoirs, and land treatment is 37 percent. However, the deposition rate in Silver Lake is reduced from 7,300 to 1,900 cu yd/year resulting in an overall sedimentation rate increase of 31 percent at the downstream limit of the project. This increase could possibly cause aggradation downstream and should be investigated by NCS.

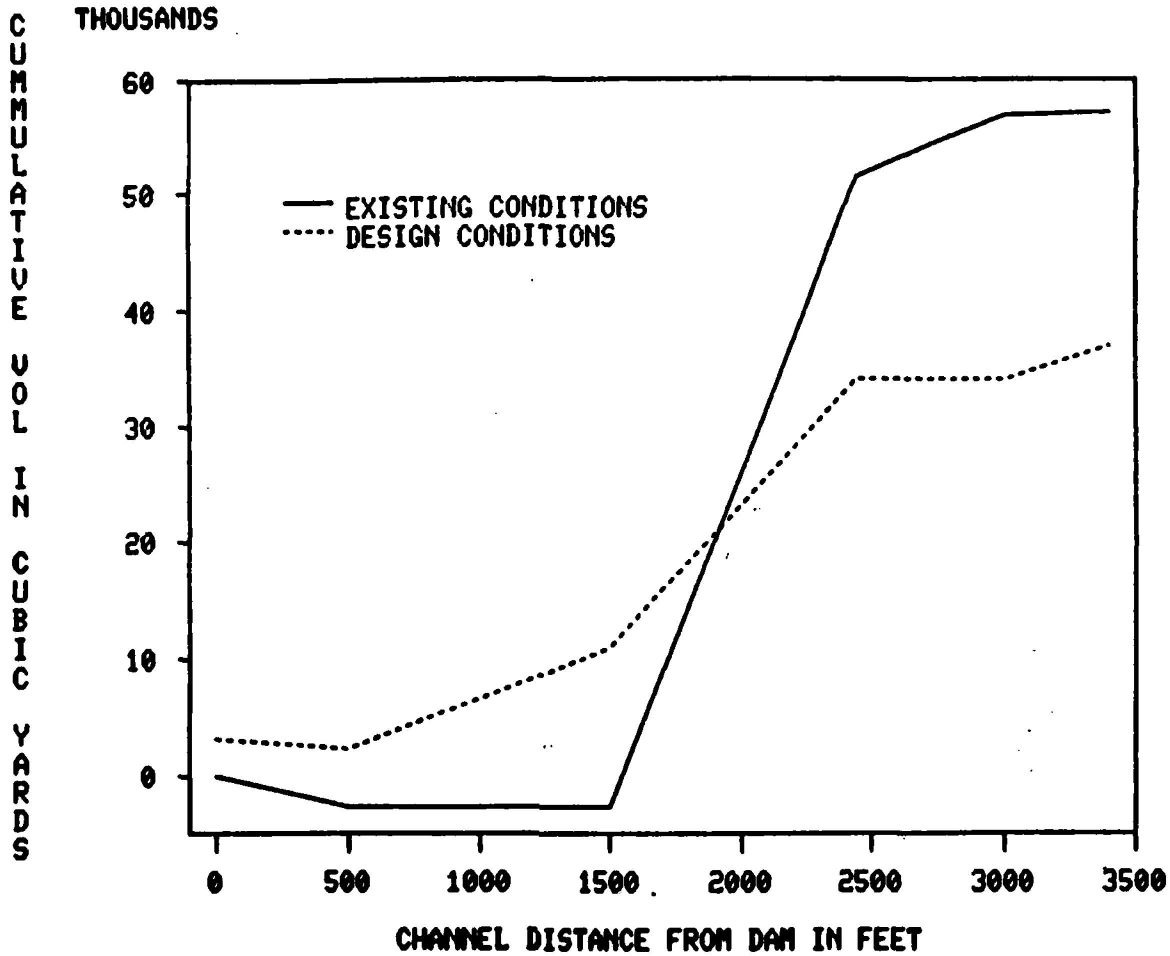


Figure 24. Distribution of deposits after 6.5-year simulation, Silver Lake

SPF Analysis of Proposed Conditions

47. The proposed condition hourly hydrograph of the SPF event was input to the model and the water-surface elevations at the peak discharge were compared with those of the existing conditions SPF event. The SPF water-surface elevations of the proposed conditions did not exceed those of the existing conditions, thereby demonstrating that the project will not increase the water-surface elevations under SPF conditions.

PART VII: SENSITIVITY ANALYSIS

Selected Hard Points Proposed Condition

48. The calibrated and verified model of proposed conditions was run with only those cross sections at rock outcrops, bridges, drop structures, and weirs modified to prevent scour. This is to simulate design riprap and gabions at these locations. Other cross sections in the design showing riprap and gabions were not hardened. This analysis was made to assess if there is a need for channel protection as shown in the design. The hydrology sequence used was the same as that used in the proposed conditions test.

49. Bear Creek results revealed extensive sediment activity, mostly scour, as shown in Figure 25. This indicates that streambed and bank protection in the design is needed.

50. Cascade Creek results showed little activity as shown in Figure 26. This implies that the proposed conditions geometry may be near the equilibrium geometry which would then suggest that the amount of riprap and/or gabions in the Cascade Creek design could be reduced and even be eliminated in some places. This possibility should be investigated by NCS.

51. The South Fork Zumbro River results, Figure 27, show extensive scour in the upper portion down to the South Broadway Bridge and this material deposited from the 4th St. Bridge to Elton Hills Bridge. The downstream area from Elton Hills Bridge results showed slight scour. These results emphasize the need for channel protection, particularly at the upper end.

Sediment Load Curve

52. Collection of suspended sediment data is subject to error from sampling techniques, equipment design, and equipment malfunction. In order to evaluate if sampling errors or erroneous predictions of the sediment load curve for proposed conditions could significantly affect the results, the proposed project conditions were simulated as described in paragraph 38 but with double and then half of the inflowing sediment discharges for the main stem and tributaries. The results are displayed in Figure 28 which shows only slight increase in deposition and decrease in scour for the double-load

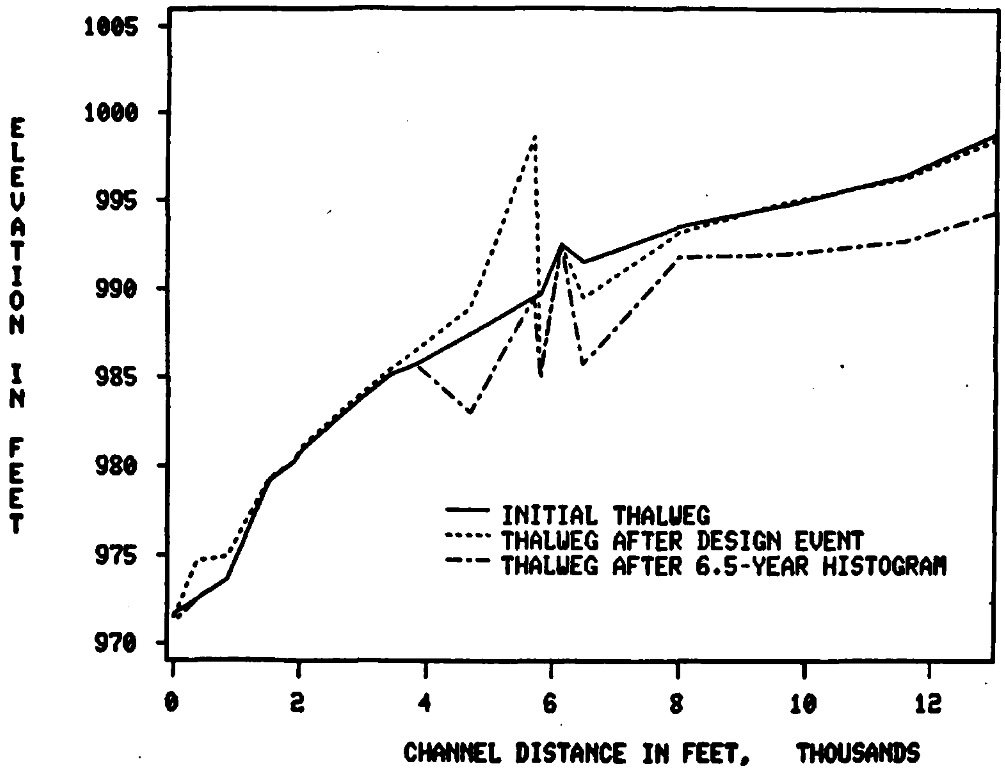


Figure 25. Bear Creek, hardened only at bedrock, drop structures, and bridges

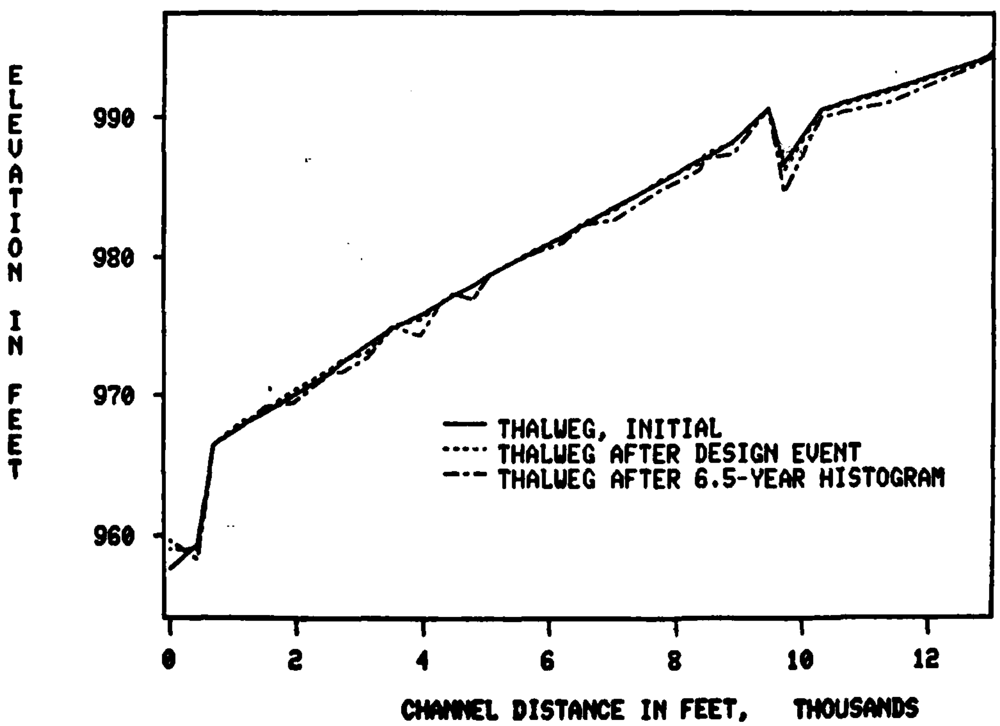


Figure 26. Cascade Creek, hardened only at bedrock, drop structures, and bridges

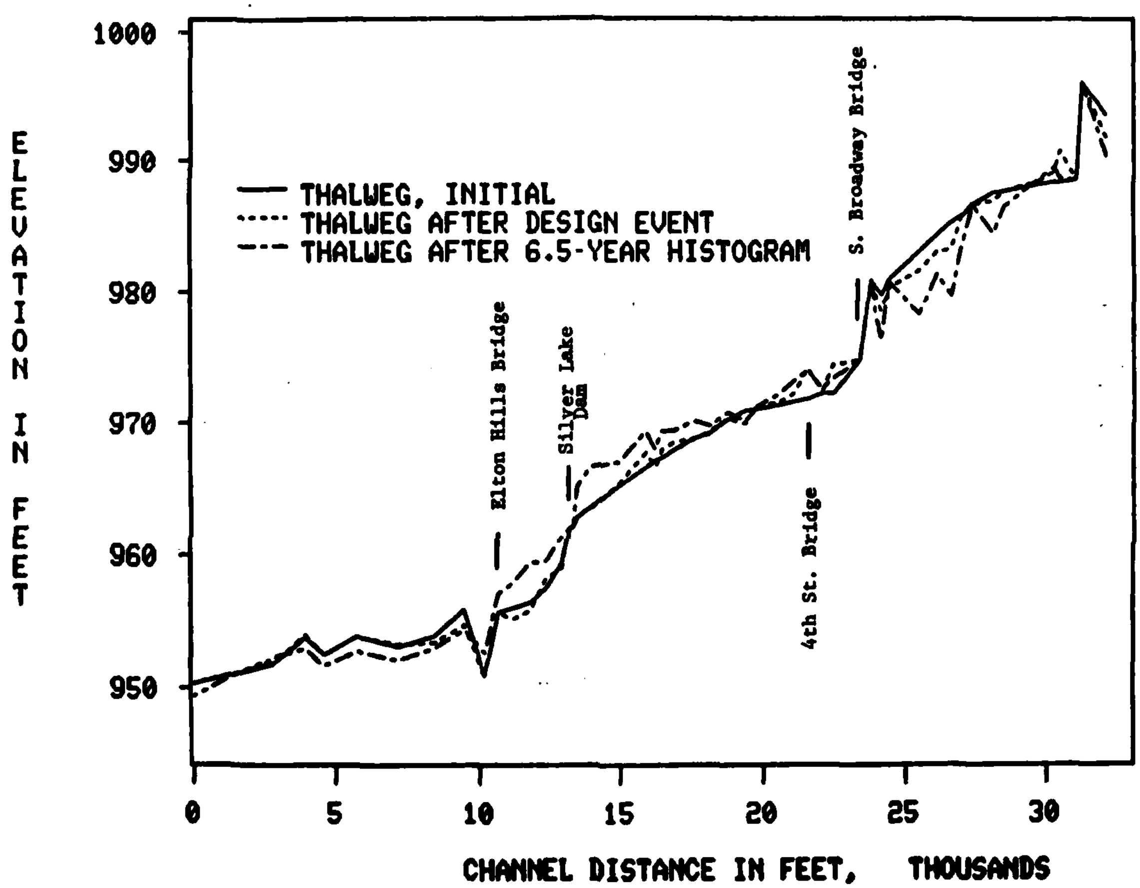


Figure 27. South Fork Zumbro River, hardened only at bedrock, drop structures, and bridges

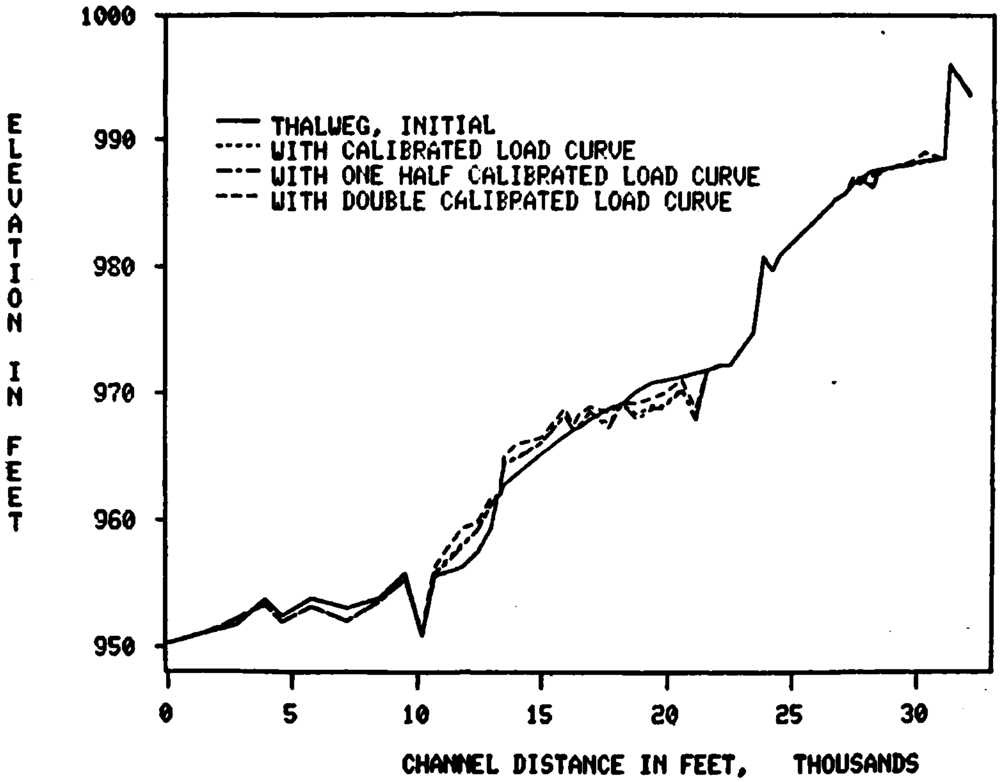


Figure 28. South Fork Zumbro River, proposed conditions

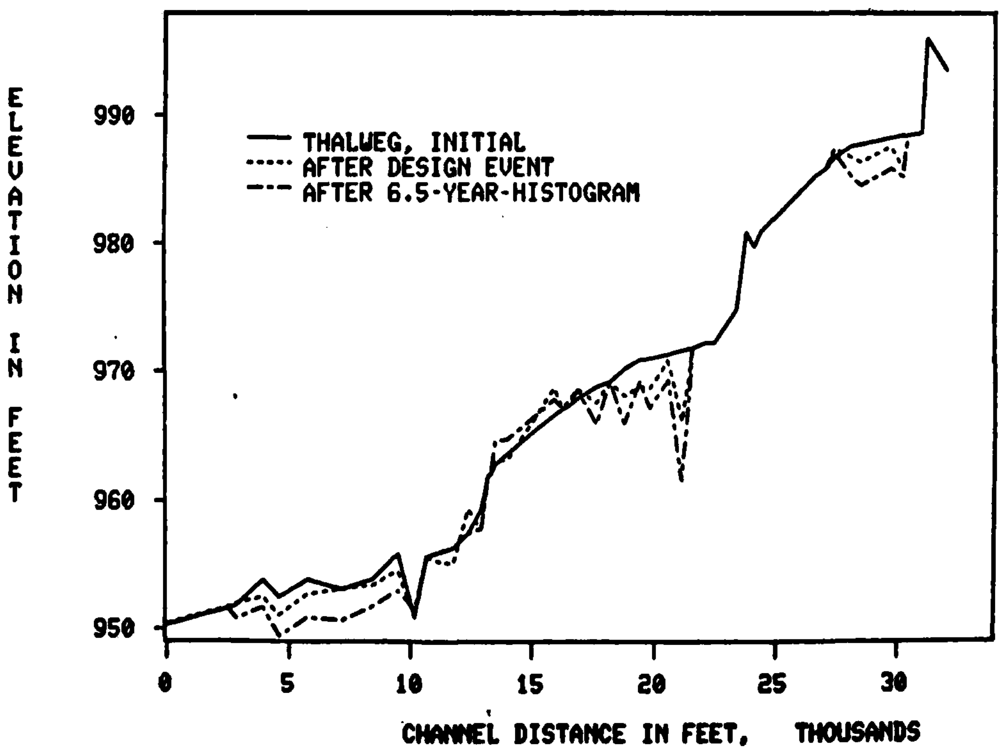


Figure 29. South Fork Zumbro River, proposed conditions, fine bed

curve, and slight decrease in deposition and increase in scour for the half-load curve. These sensitivity simulations did not cause a significant change in the discharge-elevation rating curves of the project. Bear Creek and Cascade Creek did not have significant scour or deposition.

Bed Gradation

53. HEC-6 assumes that the input bed gradation at a cross section is representative of the entire bed, vertically and laterally, for that cross section. Sometimes a sample taken at the bed surface is much coarser than the underlying material. The channelization process may remove this top layer and expose a finer gradation. To evaluate the effects of this type of situation on the results, a proposed condition simulation was made using the finest bed gradation (i.e., the smallest particle sizes) present in the base test for all the cross sections in the proposed geometry. Figure 29 shows locations where increased scour was calculated. NCS should assure that the particle sizes in the modified geometry are at least as large as those observed in the existing channel at these zones where substantial erosion is indicated.

PART VIII: SUMMARY AND RECOMMENDATIONS

Project Performance, Design Event

54. Simulation of the design event, both before and after a 6.5-year histogram, revealed no significant change in the discharge-elevation rating curve throughout the project. This assures that the design water-surface elevations for the design event will not be exceeded if the design event occurred either immediately after project implementation or after 6.5 years of simulated flow.

Project Performance, SPF Event

55. Simulation of the SPF event under proposed conditions did not significantly change the discharge-elevation rating curve during or after the event. This assures that the project will not increase flood hazards for the SPF event.

Scour Locations

56. Since the design calls for riprapping of the entire length of both Cascade and Bear Creeks except where there is a rock bottom, the only scour problems indicated by the model were in the South Fork Zumbro River. The area between the 4th St. Bridge and C&N Railroad bridge showed significant scour potential. This area has existing and proposed floodwalls on both sides of the channel. There is evidence of bedrock near the surface; however, this was from interpolation of boring samples in adjacent areas. NCS should check this area and see if there is indeed bedrock underneath and ensure that the floodwalls have adequate foundation beyond the extent of scour and/or are well keyed into the bedrock. Minor scour will occur between Elton Hills Bridge and the 37th St. Bridge but is considered insignificant.

Deposition Locations

57. Although the model showed no deposition in the channel in the Soldier's Field Golf Course, this does not necessarily mean there would not

be deposition in the overbanks. If deposition occurs, it would not be as severe as existing conditions due to the decrease in the inflowing sediment load and better sediment carrying capacity of the channel. The annual deposition rate in Silver Lake under proposed conditions will be 1,900 cu yd/yr if the reach between 4th St. and Center St. Bridges is stabilized. If not, the annual deposition rate would be 10,300 cu yd for 5 to 10 years and eventually 1,900 cu yd. The project will cause the deposition to spread farther longitudinally into Silver Lake than under existing conditions due to the change in operation of the dam.

58. Deposition occurred downstream of Silver Lake Dam during the 6.5-year simulation but was not severe enough to cause the design water-surface elevations to be exceeded.

Potential Maintenance Dredging in Channel

59. Maintenance dredging is considered to be the timely removal of deposited sediment from the channel for the purpose of conveying the design discharge such that the design water-surface elevations are not exceeded. Silver Lake deposition rate will be reduced from 7,300 to 1,900 cu yd/yr for the proposed condition under conditions mentioned in paragraph 57. This indicates an average annual maintenance reduction of 74 percent. HEC-6 predicted a deposition rate of 2,700 cu yd/yr between the Silver Lake Dam and Elton Hills Bridge.

General

60. No deposition in the channel will occur at the Apache Mall area primarily due to the effectiveness of the low-flow channels in the design. No significant deposition will occur in Cascade or Bear Creek due to the increased hydraulic and sediment transport efficiency of the proposed conditions. No scour occurs in either creek because the project calls for complete riprap of the channels, except where bedrock is exposed, from their mouths to the project limits. The annual sedimentation rate at the downstream limit of the project will increase by 31 percent and could possibly cause aggradation downstream of the project.

Recommendations

61. NCS is encouraged to establish sedimentation ranges throughout the project and at short distance intervals at locations identified as potential problem areas. These ranges should be surveyed on a periodic basis (5 to 10 years) as needed and after major events.

62. Analysis of Cascade Creek with "hardened" cross sections only at bridges and drop structures revealed a potential for reducing the amount of riprap in the design. Although it is recognized that design guidelines must be followed which may limit any changes, NCS should reevaluate the riprap design of Cascade Creek.

63. The channel maintenance described in this report does not include other types of maintenance such as periodic repair of gabions, streambank repair, and debris clearing. The use of gabions in the design must take into consideration the expected useful life versus the project life. If the useful life is less than the project life, labor intensive maintenance or repair of the gabions must be included in the cost. Considerations in determining expected useful life of gabions are salinity and pH of the water, significant differential settling, alternate wetting and drying, and attack by debris and sediment abrasion.

64. NCS should ensure that local interest will prevent the establishment of extensive vegetation in the channel. The design is generally self-cleaning but intermittent local deposition could occur and vegetation could prevent this deposition from being removed under scouring flow conditions.

65. The sediment load rate exiting the project will increase by 31 percent. NCS should investigate the possibility of adverse aggradation downstream of the project.

66. HEC-6 is a one-dimensional model; NCS must be aware of the limitations of the model and care must be taken in the interpretation of the results. For instance, the prototype may show severe scour in the channel and slight deposition in the overbanks but the model would show a net scour.

67. If changes occur in the design of the proposed condition, NCS should evaluate the effects on sediment transport by using the model with the guidance of the U. S. Army Engineer Waterways Experiment Station. The model, computer code, and all data files will be presented to NCS.

REFERENCES

Ames, Stephen C. 1975 (Oct). "Research and Recommendations Concerning National Pollutant Discharge Elimination System Permits and the Silver Lake and Broadway Generating Plants at Rochester, Minnesota," Rochester Public Utilities, City of Rochester.

Collier, C. K. 1974 (Dec). "An Approximation of Sediment Yields from Watersheds in Minnesota," presented at the 1974 Winter meeting of the American Society of Agricultural Engineers, Chicago, Ill.

Office Chief of Engineers. 1982 (Nov). Draft Chapters on "Sedimentation Manual, Chapter 4, Sediment Yield," EC 1110-2-241, Washington, D. C.

Thomas, William A. 1977a (Mar). "HEC-6, Scour and Deposition in Rivers and Reservoirs," Users Manual of Generalized Computer Program 723-62-L2470, Hydrologic Engineering Center, U. S. Army Corps of Engineers.

__________. 1977b (Sep). "Lower Granite Reservoir Version of HEC-6," U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Weldon, Chester A. 1976 (May). "South Zumbro Watershed - Geologic Report, Sediment Yields," Soil Conservation Service, Minneapolis, Minn.

__________. 1982 (Sep). "Flood Control and Related Purposes, South Fork Zumbro River, Rochester, Minnesota, Design Memorandum No. 1, Phase II - General," U. S. Army Engineer District, St. Paul, Minn.

__________. 1978 (Apr). "Watershed Plan and Environmental Impact Statement, South Zumbro Watershed, Dodge and Olmstead Counties, Minnesota," Prepared by Dodge Soil and Water Conservation District, Upper Zumbro Soil and Water Conservation District, Olmstead County Board of Commissioners, City of Rochester, published by U. S. Department of Agriculture Soil Conservation Service.